THE EQUATION $n(n+d)\cdots(n+(k-1)d) = by^2$ WITH $\omega(d) \le 6$ OR $d \le 10^{10}$

SHANTA LAISHRAM AND T. N. SHOREY

Abstract. For relatively prime positive integers n and d, a well-known Conjecture states that $n(n+d)\cdots(n+(k-1)d)$ with $k \ge 4$ is never a square. The first result is due to Euler for $k = 4$. We confirm the conjecture when $d \le 10^{10}$ or d has at most five prime divisors.

1. Introduction

For an integer $x > 1$, we denote by $P(x)$ and $\omega(x)$ the greatest prime factor of x and the number of distinct prime divisors of x, respectively. Further we put $P(1) = 1$ and $\omega(1) = 0$. The letter p always denote a prime number and p_i the $i-$th prime number. Let n, d, k, b and y be positive integers such that b is square free, $k \ge 2$, $P(b) \le k$ and $\gcd(n, d) = 1$. We consider the equation

$$n(n+d)\cdots(n+(k-1)d) = by^2 \text{ in } n, d, k, b, y. \tag{1.1}$$

If $d = 1$, then (1.1) has been completely solved for $P(b) < k$ by Erdős and Selfridge [ErSe75] and for $P(b) = k$ by Saradha [Sar97]. Therefore we always suppose that $d > 1$. We observe that (1.1) has infinitely many solutions if $k = 2, 3$ and $b = 1$. Also (1.1) with $k = 4$ implies that $b = 6$. Therefore we always suppose that $k \ge 5$ if we consider (1.1) and $k \ge 4$ if we consider (1.1) with $b = 1$. It has been conjectured that (1.1) with $k \ge 5$ does not hold. A weaker version due to Erdős states that (1.1) implies that k is bounded by an absolute constant. This has been confirmed by Marszalek [Mar85] when d is fixed and by Shorey and Tijdeman [ShTi90] when $\omega(d)$ is fixed. In fact Shorey and Tijdeman [ShTi90] proved that (1.1) implies that

$$2^{\omega(d)} > c_1 \frac{k}{\log k} \tag{1.2}$$

which gives

$$d > k^{c_2 \log\log k}$$

where $c_1 > 0$ and $c_2 > 0$ are absolute constants. Laishram [Lai06] gave an explicit version of (1.2) by showing

$$k < 11\omega(d)4^{\omega(d)} \text{ if } \omega(d) \ge 12 \tag{1.3}$$

and we improve

$$k < 2\omega(d)2^{\omega(d)}, \tag{1.4}$$

see Corollary 8.7 when $\omega(d) \ge 5$ and Theorem 3 when $\omega(d) < 5$ for a precise formulation. Equation (1.1) has been completely solved in Saradha and Shorey [SaSh03a] for $d \le 104$ and $k \ge 4$. We prove

Theorem 1. *Equation* (1.1) *with* $k \ge 6$ *implies that*

$$d > \max(10^{10}, k^{\log\log k}).$$

2000 Mathematics Subject Classification Primary 11D61

Keywords: Diophantine equations, Arithmetic Progressions, Squares, Legendre symbol, squarefree integers, Congruences.

For a given value of d, we observe that (1.1) with $k \in \{4, 5\}$ can be solved via finding all the integral points on elliptic curves by MAGMA or SIMATH as in [FiHa01] and [SaSh03a]. Analogous results on higher powers for (1.1) with $k \geq 4$ and y^2 replaced by y^ℓ where $\ell > 2$ is prime are proved in Saradha and Shorey [SaSh05]; they showed that $d > 30, 5 \cdot 10^4, 10^8$ and 10^{15} according as $\ell = 3, 5, 7$ and ≥ 11, respectively. For Theorem 1, we prove several results on (1.1) which are of independent interest. For example, we solve (1.1) when $\omega(d) \leq 5, b = 1$ or $\omega(d) \leq 4$. We prove

Theorem 2. *Equation* (1.1) *with* $b = 1$ *and* $\omega(d) \leq 5$ *does not hold.*

Theorem 2 contains the case $\omega(d) = 1$ already proved by Saradha and Shorey [SaSh03a]. In fact they proved it without the assumption $\gcd(n, d) = 1$. We show that this is also not required when $\omega(d) = 2$ and $k \geq 8$, see Section . We derive Theorem 2 from a more general result and we turn to introducing some notation for it.

From (1.1), we have

$$n + id = a_i x_i^2 \text{ for } 0 \leq i < k \tag{1.5}$$

where a_i's are square free such that $P(a_i) \leq \max(P(b), k-1) \leq k$. Thus (1.1) with b as the squarefree part of $a_0 a_1 \cdots a_{k-1}$ is determined by the $k-$tuple $(a_0, a_1, \cdots, a_{k-1})$. We rewrite (1.1) as

$$N(N-d)\cdots(N-(k-1)d) = by^2, \ N = n + (k-1)d. \tag{1.6}$$

We call (1.6) as the mirror image of (1.1). It is completely determined by $(a_{k-1}, \cdots, a_0)$ which we call as the mirror image of $(a_0, \cdots, a_{k-1})$. Let $\mathfrak{S}_1$ be the set of tuples $(a_0, \cdots, a_{k-1})$ given by

$$k = 8 : (2, 3, 1, 5, 6, 7, 2, 1), (3, 1, 5, 6, 7, 2, 1, 10);$$

$$k = 9 : (2, 3, 1, 5, 6, 7, 2, 1, 10);$$

$$k = 13 : (3, 1, 5, 6, 7, 2, 1, 10, 11, 3, 13, 14, 15), (1, 5, 6, 7, 2, 1, 10, 11, 3, 13, 14, 15, 1)$$

and their mirror images. Further $\mathfrak{S}_2$ be the set of tuples $(a_0, a_1, \cdots, a_{k-1})$ given by

$$k = 14 : (3, 1, 5, 6, 7, 2, 1, 10, 11, 3, 13, 14, 15, 1);$$

$$k = 19 : (1, 5, 6, 7, 2, 1, 10, 11, 3, 13, 14, 15, 1, 17, 2, 19, 5, 21, 22);$$

$$k = 23 : (5, 6, 7, 2, 1, 10, 11, 3, 13, 14, 15, 1, 17, 2, 19, 5, 21, 22, 23, 6, 1, 26, 3),$$

$$(6, 7, 2, 1, 10, 11, 3, 13, 14, 15, 1, 17, 2, 19, 5, 21, 22, 23, 6, 1, 26, 3, 7);$$

$$k = 24 : (5, 6, 7, 2, 1, 10, 11, 3, 13, 14, 15, 1, 17, 2, 19, 5, 21, 22, 23, 6, 1, 26, 3, 7)$$

and their mirror images.

Equation (1.1) with $k = 6$ is not possible by Bennett, Bruin, Győry and Hajdu [BBGH06]. Also (1.1) with $k \in \{5, 7\}$ and $P(b) < k$ does not hold by Mukhopadhyay and Shorey [MuSh03] for $k = 5$ and Hirata-Kohno, Laishram, Shorey and Tijdeman [HiLaShTi06] for $k = 7$. We do not have any contribution for the cases $k \in \{5, 7\}$ and $P(b) = k$ in the next result where we solve all the equations (1.1) other than the ones given by $\mathfrak{S}_1 \cup \mathfrak{S}_2$ whenever $\omega(d) \leq 4$ and therefore we assume $k \geq 8$ in Theorem 3 (a). More precisely, we prove

Theorem 3. (a) *Equation* (1.1) *with* $k \geq 8$ *and* $\omega(d) \leq 4$ *implies that either* $\omega(d) = 2, k = 8,$ $(a_0, a_1, \cdots, a_7) \in \{(3, 1, 5, 6, 7, 2, 1, 10), (10, 1, 2, 7, 6, 5, 1, 3)\}$ *or* $\omega(d) = 3,$ $(a_0, a_1, \cdots, a_{k-1}) \in \mathfrak{S}_1$ *or* $\omega(d) = 4, (a_0, a_1, \cdots, a_{k-1}) \in \mathfrak{S}_1 \cup \mathfrak{S}_2$.

(*b*) *Equation* (1.1) *with* $\omega(d)\in\{5,6\}$ *and* d *even does not hold.*

Theorem 3 contains already proved case $\omega(d)=1$ where it has been shown in [SaSh03a] for $k>29$ and [MuSh03] for $4\le k\le 29$ that (1.1) implies that either $k=4,(n,d,b,y)=(75,23,6,140)$ or $k=5,P(b)=k$. The next result shows that it suffices to prove our Theorems 1 and 3 for $k\ge 101$ unless (1.1) is given by $\mathfrak{S}$ which is the union of $\mathfrak{S}_1,\mathfrak{S}_2$ and set of tuples given by $k=7,(a_0,a_1,\cdots,a_{k-1})\in\{(2,3,1,5,6,7,2),(3,1,5,6,7,2,1),(1,5,6,7,2,1,10)\}$ and their mirror images.

Theorem $\mathcal{A}$. (*a*) *Equation* (1.1) *with* $7\le k\le 100$ *is not possible unless* $(a_0,a_1,\cdots,a_{k-1})\in\mathfrak{S}$.
(*b*) *Equation* (1.1) *with* $4\le k\le 109$ *and* $b=1$ *does not hold.*

This is due to Hirata-Kohno, Laishram, Shorey and Tijdeman [HiLaShTi06]. For a survey of related results, see [Sho02].

2. Notations and Preliminaries

Let $k\ge 4$ and $\gamma_1<\gamma_2<\cdots<\gamma_t$ be integers with $0\le\gamma_i<k$ for $1\le i\le t$. We consider a more general equation

$$(n+\gamma_1 d)\cdots(n+\gamma_t d)=by^2 \tag{2.1}$$

in positive integers n,d,k,b,y,t with b squarefree, $P(b)\le k$ and $\gcd(n,d)=1$. If $t=k$, we observe that $\gamma_i=i-1$ and (2.1) coincides with (1.1). It is of interest to consider more general equation (2.1) because of possible applications. Assume that (2.1) holds. Then we have

$$n+\gamma_i d=a_{\gamma_i}x_{\gamma_i}^2 \text{ for } 1\le i\le t \tag{2.2}$$

with a_{γ_i} squarefree such that $P(a_{\gamma_i})\le k$. Also

$$n+\gamma_i d=A_{\gamma_i}X_{\gamma_i}^2 \text{ for } 1\le i\le t \tag{2.3}$$

$P(A_{\gamma_i})\le k$ and $\gcd(X_{\gamma_i},\prod_{p\le k}p)=1$. Further we write

$$b_i=a_{\gamma_i},\ B_i=A_{\gamma_i},\ y_i=x_{\gamma_i},\quad Y_i=X_{\gamma_i}.$$

Since $\gcd(n,d)=1$, we see from (2.2) and (2.3) that

$$(b_i,d)=(B_i,d)=(y_i,d)=(Y_i,d)=1 \text{ for } 1\le i\le t. \tag{2.4}$$

Let

$$R=\{b_i:1\le i\le t\}.$$

For $b_i\in R$, let $\nu(b_i)=|\{j:1\le j\le t,b_j=b_i\}|$ and

$$\nu_o(b_i)=|\{j:1\le j\le t,b_j=b_i,2\nmid y_j\}|,\ \nu_e(b_i)=|\{j:1\le j\le t,b_j=b_i,2|y_j\}|.$$

We define

$$R_\mu=\{b_i\in R:\nu(b_i)=\mu\},\quad r_\mu=|R_\mu|,\quad \mathfrak{r}=\left|\{(i,j):b_i=b_j,i>j\}\right|.$$

Let

$$T=\{1\le i\le t:Y_i=1\},\ T_1=\{1\le i\le t:Y_i>1\},\ S_1=\{B_i:i\in T_1\}.$$

Note that $Y_i > k$ for $i \in T_1$. For $i \in T_1$, we denote by $\nu(B_i) = |\{j \in T_1 : B_j = B_i\}|$.

Let

$$\delta = \min(3, \mathrm{ord}_2(d)),\ \delta' = \min(1, \mathrm{ord}_2(d)), \tag{2.5}$$

$$\eta = \begin{cases} 1 & \text{if } \mathrm{ord}_2(d) \leq 1, \\ 2 & \text{if } \mathrm{ord}_2(d) \geq 2 \end{cases} \tag{2.6}$$

and

$$\rho = \begin{cases} 3 & \text{if } 3|d, \\ 1 & \text{if } 3 \nmid d. \end{cases} \tag{2.7}$$

Let $d^{'}|d$ and $d^{''} = \frac{d}{d'}$ be such that $\gcd(d^{'}, d^{''}) = 1$. We write

$$d^{''} = d_1 d_2,\ \gcd(d_1, d_2) = \begin{cases} 1 & \text{if } \mathrm{ord}_2(d^{''}) \leq 1 \\ 2 & \text{if } \mathrm{ord}_2(d^{''}) \geq 2 \end{cases}$$

and we always suppose that d_1 is odd if $\mathrm{ord}_2(d^{''}) = 1$. We call such pairs (d_1, d_2) as partitions of $d^{''}$. We observe that the number of partitions of $d^{''}$ is $2^{\omega(d^{''})-\theta_1}$ where

$$\theta_1 := \theta_1(d^{''}) = \begin{cases} 1 & \text{if } \mathrm{ord}_2(d^{''}) = 1, 2 \\ 0 & \text{otherwise} \end{cases}$$

and we write θ for $\theta_1(d)$. In particular, by taking $d' = 1$ and $d^{''} = d$, the number of partitions of d is $2^{\omega(d)-\theta}$.

Let $b_i = b_j, i > j$. Then from (2.2) and (2.4), we have

$$\frac{(\gamma_i - \gamma_j)}{b_i} d^{'} = \frac{y_i^2 - y_j^2}{d''} = \frac{(y_i - y_j)(y_i + y_j)}{d''}. \tag{2.8}$$

such that $\gcd(d^{''}, y_i - y_j, y_i + y_j) = 1$ if $d^{''}$ is odd and 2 if $d^{''}$ is even. Thus a pair (i, j) with $i > j$ and $b_i = b_j$ corresponds to a partition (d_1, d_2) of $d^{''}$ such that $d_1 \mid (y_i - y_j)$, $d_2 \mid (y_i + y_j)$ and it is unique. Similarly, we have unique partition of $d^{''}$ corresponding to every pair (i, j) whenever $B_i = B_j$, $i, j \in T_1$.

Let $\mathfrak{p}_1 < \mathfrak{p}_2 < \cdots$ be the odd primes dividing d. Let

$$d = \begin{cases} 2^{\delta} \mathfrak{q}_1 \mathfrak{q}_2 \cdots \mathfrak{q}_{\omega(d)-1} & \text{if } \delta = 1, 2 \\ \mathfrak{q}_1 \mathfrak{q}_2 \cdots \mathfrak{q}_{\omega(d)} & \text{otherwise} \end{cases}$$

where $\mathfrak{q}_1 < \mathfrak{q}_2 < \cdots \mathfrak{q}_{\omega(d)-\theta}$ are prime powers dividing $\frac{d}{2^{\delta\theta}}$. By induction, we have

$$\mathfrak{p}_1 \mathfrak{p}_2 \cdots \mathfrak{p}_h \leq \mathfrak{q}_1 \mathfrak{q}_2 \cdots \mathfrak{q}_h \leq \left(\frac{d}{2^{\delta\theta}}\right)^{\frac{h}{\omega(d)-\theta}} \tag{2.9}$$

for any h with $1 \leq h \leq \omega(d) - \theta$. Further we define

$$\mathcal{A}_h = \{B_i \in T_1 : B_i < \mathfrak{q}_1 \mathfrak{q}_2 \cdots \mathfrak{q}_h\}, \quad \lambda_h = |\mathcal{A}_h|. \tag{2.10}$$

for any h with $1 \leq h \leq \omega(d) - \theta$.

3. Upper bound for $n + (k-1)d$

In this section, we assume that (2.1) holds. Let $i > j, g > h, 0 \leq i, j, g, h < k$ be such that

$$b_i = b_j,\ b_g = b_h,\ \gamma_i + \gamma_j \geq \gamma_g + \gamma_h \tag{3.1}$$

and

$$y_i - y_j = d_1 r_1,\ y_i + y_j = d_2 r_2,\ y_g - y_h = d_1 s_1,\ y_g + y_h = d_2 s_2 \tag{3.2}$$

where (d_1,d_2) is a partition of d. We write $V(i,j,g,h,d_1,d_2)$ for such double pairs. We call $V(i,j,g,h,d_1,d_2)$ degenerate if

$$b_i=b_g, r_1=s_1 \text{ or } \; b_i=b_g, r_2=s_2. \tag{3.3}$$

Otherwise we call it non-degenerate. Let q_1 and q_2 be given by

$$|b_ir_1^2-b_gs_1^2|=q_1d_2 \text{ and } |b_ir_2^2-b_gs_2^2|=q_2d_1. \tag{3.4}$$

We shall also write $V(i,j,g,h,d_1,d_2)=V(i,j,g,h,d_1,d_2,q_1,q_2)$.

Let Ω be a set of pairs (i,j) with $i>j$ such that $b_i=b_j$. Then we say that Ω has *Property ND* if the the following holds: For any two distinct pairs (i,j) and (g,h) in Ω corresponding to a partition (d_1,d_2) of d, the double pair $V(i,j,g,h,d_1,d_2)$ is non-degenerate.

In this section, we give upper bound for $n+(k-1)d$ whenever it is possible to find a non-degenerate double pair. The next section gives lower bound for $n+(k-1)d$. As in [ShTi90], the proof of our theorems depend on showing that the upper bound and lower bound for $n+(k-1)d$ are not consistent whenever it is possible to find a non-degenerate double pair. Further we show in this section that this is always the case whenever $k-|R|\ge 2^{\omega(d)-\theta}$. If we do not have this, we use Lemmas 5.4 and 7.6 depending on an idea of Erdős to give an upper bound for k. Thus there are only finitely many possibilities for k and we use counting arguments given in Section 6 to exclude these possibilities. For example, we show in Lemma 7.5 that k is large whenever d is divisible by two small primes. This is very useful in our proofs and increases considerably a lower bound for d in Theorem 1. The computations in this paper were carried out using MATHEMATICA.

We begin with the following result.

Lemma 3.1. *Let $d=\theta_1(k-1)^2, n=\theta_2(k-1)^3$ with $\theta_1>0$ and $\theta_2>0$. Let $V(i,j,g,h,d_1,d_2,q_1,q_2)$ be a non-degenerate double pair. Then*

$$\theta_2<\frac{1}{2}\left\{\frac{1}{q_1q_2}-\theta_1+\sqrt{\frac{1}{(q_1q_2)^2}+\frac{\theta_1}{q_1q_2}}\right\} \tag{3.5}$$

and

$$d_1<\frac{\theta_1(k-1)}{q_1(2\theta_2+\theta_1)},\; d_2<\frac{4(k-1)}{q_2}. \tag{3.6}$$

Proof. We have from (3.2) that $y_i=\frac{d_1r_1+d_2r_2}{2}$ and $y_g=\frac{d_1s_1+d_2s_2}{2}$. Further from (2.2) and (3.1), we get

$$(\gamma_i-\gamma_g)d=b_iy_i^2-b_gy_g^2=\frac{1}{4}\left\{(b_ir_1^2-b_gs_1^2)d_1^2+(b_ir_2^2-b_gs_2^2)d_2^2+2d(b_ir_1r_2-b_gs_1s_2)\right\}.$$

We observe from (3.2), (3.1) and (2.2) that $b_ir_1r_2=\gamma_i-\gamma_j, b_gs_1s_2=\gamma_g-\gamma_h$. Therefore

$$2(\gamma_i+\gamma_j-\gamma_g-\gamma_h)d=(b_ir_1^2-b_gs_1^2)d_1^2+(b_ir_2^2-b_gs_2^2)d_2^2. \tag{3.7}$$

Then reading modulo d_1,d_2 separately in (3.7), we have

$$\begin{aligned} &d_2\Big|(b_ir_1^2-b_gs_1^2),\; d_1\Big|(b_ir_2^2-b_gs_2^2) \text{ if } \mathrm{ord}_2(d)\le 1\\ &\frac{d_2}{2}\Big|(b_ir_1^2-b_gs_1^2),\; \frac{d_1}{2}\Big|(b_ir_2^2-b_gs_2^2) \text{ if } \mathrm{ord}_2(d)\ge 2. \end{aligned} \tag{3.8}$$

Hence $2q_1, 2q_2$ are non-negative integers. We see that $q_1 \neq 0$ and $q_2 \neq 0$ since $V(i,j,g,h,d_1,d_2,q_1,q_2)$ is non-degenerate. Further we see from (2.2) that

$$b_iy_i^2 - b_gy_g^2 = (\gamma_i - \gamma_g)d, \quad b_jy_j^2 - b_hy_h^2 = (\gamma_j - \gamma_h)d. \tag{3.9}$$

Therefore, by (3.2), we have

$$\begin{aligned} 0 \neq F_1 := (b_ir_1^2 - b_gs_1^2)d_1^2 &= b_i(y_i - y_j)^2 - b_g(y_g - y_h)^2 \\ &= (\gamma_i + \gamma_j - \gamma_g - \gamma_h)d - 2(b_iy_iy_j - b_gy_gy_h) \end{aligned} \tag{3.10}$$

and

$$\begin{aligned} 0 \neq F_2 := (b_ir_2^2 - b_gs_2^2)d_2^2 &= b_i(y_i + y_j)^2 - b_g(y_g + y_h)^2 \\ &= (\gamma_i + \gamma_j - \gamma_g - \gamma_h)d + 2(b_iy_iy_j - b_gy_gy_h). \end{aligned} \tag{3.11}$$

We note here that $F_1 < 0, F_2 < 0$ is not possible since $\gamma_i + \gamma_j \geq \gamma_g + \gamma_h$.

Let a and b be positive real numbers with $a \neq b$. We have $2\sqrt{ab} = (a+b)(1 - (\frac{a-b}{a+b})^2)^{\frac{1}{2}}$. By using $1 - x < (1-x)^{\frac{1}{2}} < 1 - \frac{x}{2}$ for $0 < x < 1$, we get $a + b - \frac{(a-b)^2}{a+b} < 2\sqrt{ab} < a + b - \frac{(a-b)^2}{2(a+b)}$. We use it with $a = n + \gamma_i d$ and $b = n + \gamma_j d$ so that $\sqrt{ab} = b_iy_iy_j$ by (2.2) and (3.1). We obtain

$$2n + (\gamma_i + \gamma_j)d - \frac{(\gamma_i - \gamma_j)^2d^2}{2n + (\gamma_i + \gamma_j)d} < 2b_iy_iy_j < 2n + (\gamma_i + \gamma_j)d - \frac{(\gamma_i - \gamma_j)^2d^2}{4n + 2(\gamma_i + \gamma_j)d}. \tag{3.12}$$

Similarly we get

$$2n + (\gamma_g + \gamma_h)d - \frac{(\gamma_g - \gamma_h)^2d^2}{2n + (\gamma_g + \gamma_h)d} < 2b_gy_gy_h < 2n + (\gamma_g + \gamma_h)d - \frac{(\gamma_g - \gamma_h)^2d^2}{4n + 2(\gamma_g + \gamma_h)d}. \tag{3.13}$$

Therefore we have from (3.4), (3.10), (3.12) and (3.13) that

$$\begin{aligned} q_1dd_1 <& (\gamma_i + \gamma_j - \gamma_g - \gamma_h)d - (2n + (\gamma_i + \gamma_j)d) + \frac{(\gamma_i - \gamma_j)^2d^2}{2n + (\gamma_i + \gamma_j)d} \\ &+ (2n + (\gamma_g + \gamma_h)d) - \frac{(\gamma_g - \gamma_h)^2d^2}{4n + 2(\gamma_g + \gamma_h)d} \text{ if } F_1 > 0 \end{aligned}$$

and

$$\begin{aligned} q_1dd_1 <& (2n + (\gamma_i + \gamma_j)d) - \frac{(\gamma_i - \gamma_j)^2d^2}{4n + 2(\gamma_i + \gamma_j)d} - (2n + (\gamma_g + \gamma_h)d) \\ &+ \frac{(\gamma_g - \gamma_h)^2d^2}{2n + (\gamma_g + \gamma_h)d} - (\gamma_i + \gamma_j - \gamma_g - \gamma_h)d \text{ if } F_1 < 0. \end{aligned}$$

Thus

$$q_1d_1 < \begin{cases} \frac{(\gamma_i - \gamma_j)^2d}{2n + (\gamma_i + \gamma_j)d} = \frac{\theta_1(\gamma_i - \gamma_j)^2}{2\theta_2(k-1) + \theta_1(\gamma_i + \gamma_j)} & \text{if } F_1 > 0, \\ \frac{(\gamma_g - \gamma_h)^2d}{2n + (\gamma_g + \gamma_h)d} = \frac{\theta_1(\gamma_g - \gamma_h)^2}{2\theta_2(k-1) + \theta_1(\gamma_g + \gamma_h)} & \text{if } F_1 < 0. \end{cases} \tag{3.14}$$

Similarly from (3.4), (3.11), (3.12) and (3.13), we have

$$q_2d_2 < \begin{cases} 2(\gamma_i + \gamma_j - \gamma_g - \gamma_h) + \frac{\theta_1(\gamma_g - \gamma_h)^2}{2\theta_2(k-1) + \theta_1(\gamma_g + \gamma_h)} & \text{if } F_2 > 0 \\ \frac{\theta_1(\gamma_i - \gamma_j)^2}{2\theta_2(k-1) + \theta_1(\gamma_i + \gamma_j)} - 2(\gamma_i + \gamma_j - \gamma_g - \gamma_h) & \text{if } F_2 < 0. \end{cases} \tag{3.15}$$

Let

$$n_{i,j} := (k-1)^2 \left\{ \theta_2(k-1) + \frac{\theta_1(\gamma_i + \gamma_j)}{2} - \frac{\theta_1^2(\gamma_i - \gamma_j)^2}{2(2\theta_2(k-1) + \theta_1(\gamma_i + \gamma_j))} \right\}$$

and

$$n_{g,h} := (k-1)^2 \left\{ \theta_2(k-1) + \frac{\theta_1(\gamma_g + \gamma_h)}{2} - \frac{\theta_1^2(\gamma_g - \gamma_h)^2}{2(2\theta_2(k-1) + \theta_1(\gamma_g + \gamma_h))} \right\}.$$

Then we see from (3.12) and (3.13) that $n_{i,j} < b_iy_iy_j < \frac{1}{4}b_i(y_i+y_j)^2$ and $n_{g,h} < b_gy_gy_h < \frac{1}{4}b_g(y_g+y_h)^2$, respectively. Assume $F_1 > 0$. Then from (3.4), (3.11) and (3.2), we have

$$n_{i,j}q_1d_2d_1^2 < \frac{1}{4}b_i(y_i+y_j)^2b_i(y_i-y_j)^2 = \frac{1}{4}(\gamma_i-\gamma_j)^2d^2$$

implying

$$\begin{aligned}\theta_1+\theta_2 &= \frac{n_{i,j}}{(k-1)^3}+\frac{\theta_1}{k-1}\left(k-1-\frac{\gamma_i+\gamma_j}{2}+\frac{\theta_1(\gamma_i-\gamma_j)^2}{2(2\theta_2(k-1)+\theta_1(\gamma_i+\gamma_j))}\right)\\ &< \frac{(\gamma_i-\gamma_j)^2}{4q_1(k-1)^3}d_2+\theta_1 \le \frac{d_2}{4q_1(k-1)}+\theta_1 \text{ if } F_1>0\end{aligned} \tag{3.16}$$

by estimating $\frac{\theta_1(\gamma_i-\gamma_j)^2}{2(2\theta_2(k-1)+\theta_1(\gamma_i+\gamma_j))} \le \frac{(\gamma_i-\gamma_j)^2}{2(\gamma_i+\gamma_j)} < \frac{\gamma_i+\gamma_j}{2}$. Similarly

$$\theta_1+\theta_2 < \frac{d_2}{4q_1(k-1)}+\theta_1 \text{ if } F_1<0. \tag{3.17}$$

We separate the possible cases:

Case I: Let $F_1>0, F_2>0$. From (3.14) and (3.15), we have

$$\begin{aligned}q_1q_2\theta_1(k-1)^2 <&\frac{\theta_1(\gamma_i-\gamma_j)^2}{2\theta_2(k-1)+\theta_1(\gamma_i+\gamma_j)}\left\{2(\gamma_i+\gamma_j-\gamma_g-\gamma_h)+\frac{\theta_1(\gamma_g-\gamma_h)^2}{2\theta_2(k-1)+\theta_1(\gamma_g+\gamma_h)}\right\}\\ <&\frac{\theta_1(\gamma_i-\gamma_j)^2}{2\theta_2(k-1)+\theta_1(\gamma_i+\gamma_j)}\left\{2(\gamma_i+\gamma_j)-2(\gamma_g+\gamma_h)+\gamma_g-\gamma_h\right\}\\ <&\frac{2\theta_1(\gamma_i-\gamma_j)^2(\gamma_i+\gamma_j)}{2\theta_2(k-1)+\theta_1(\gamma_i+\gamma_j)} \le \frac{2\theta_1\gamma_i^3}{2\theta_2(k-1)+\theta_1\gamma_i} \le \frac{2\theta_1(k-1)^3}{2\theta_2(k-1)+\theta_1(k-1)}\end{aligned}$$

since $\frac{2\theta_1\gamma_i^3}{2\theta_2(k-1)+\theta_1\gamma_i^3}$ is an increasing function of γ_i. Therefore $2\theta_2+\theta_1 < \frac{2}{q_1q_2}$ which gives (3.5). Further from (3.14) and (3.15), we have

$$d_1 < \frac{\theta_1(\gamma_i-\gamma_j)^2}{q_1(2\theta_2(k-1)+\theta_1(\gamma_i+\gamma_j))} < \frac{\theta_1\gamma_i^2}{q_1(2\theta_2(k-1)+\theta_1\gamma_i)} \le \frac{\theta_1(k-1)}{q_1(2\theta_2+\theta_1)}$$

and

$$d_2 < \frac{1}{q_2}\left\{2(\gamma_i+\gamma_j)-2(\gamma_g+\gamma_h)+\gamma_g-\gamma_h\right\} < \frac{2(\gamma_i+\gamma_j)}{q_2} < \frac{4(k-1)}{q_2}$$

giving (3.6).

Case II: Let $F_1>0, F_2<0$. From (3.14), we have

$$d_1 < \frac{\theta_1(\gamma_i-\gamma_j)^2}{q_1(2\theta_2(k-1)+\theta_1(\gamma_i+\gamma_j))} < \frac{\theta_1(k-1)}{q_1(2\theta_2+\theta_1)}.$$

Similarly $d_2 < \frac{1}{q_2}\frac{\theta_1(k-1)}{2\theta_2+\theta_1} < \frac{k-1}{q_2}$ from (3.15) and $\gamma_i+\gamma_j \ge \gamma_g+\gamma_h$. Therefore (3.6) follows. Further

$$\theta_1(k-1)^2 = d = d_1d_2 < \frac{\theta_1^2(k-1)^2}{q_1q_2(2\theta_2+\theta_1)^2}$$

implying $(2\theta_2+\theta_1)^2 < \frac{\theta_1}{q_1q_2}$. Hence (3.5) follows.

Case III: Let $F_1<0, F_2>0$. From (3.14) and (3.15), we have

$$\theta_1(k-1)^2 < \frac{\theta_1\gamma_g^2}{q_1q_2(2\theta_2(k-1)+\theta_1\gamma_g)}\left\{2(\gamma_i+\gamma_j-\gamma_g)+\frac{\theta_1\gamma_g^2}{2\theta_2(k-1)+\theta_1\gamma_g}\right\}.$$

Let $\chi(\gamma_g) = 1 - \frac{2\theta_2(k-1)}{2\theta_2(k-1)+\theta_1\gamma_g}$ so that $\gamma_g\chi(\gamma_g) = \frac{\theta_1\gamma_g^2}{2\theta_2(k-1)+\theta_1\gamma_g} \leq \frac{\theta_1(k-1)}{2\theta_2+\theta_1}$ and both $\chi(\gamma_g)$ and $\gamma_g\chi(\gamma_g)$ are increasing functions of γ_g. Since $\gamma_i + \gamma_j \leq 2(k-1)$, we have

$$\begin{aligned}\theta_1(k-1)^2 &< \frac{\gamma_g\chi(\gamma_g)}{q_1q_2}\{2(2(k-1)-\gamma_g)+\gamma_g\chi(\gamma_g)\}\\ &< \frac{\chi(\gamma_g)}{q_1q_2}\left\{2\gamma_g(2(k-1)-\gamma_g)+\gamma_g^2\chi(\gamma_g)\right\}.\end{aligned}$$

We see that $\gamma_g(2(k-1)-\gamma_g)$ is an increasing function of γ_g since $\gamma_g \leq k-1$. Therefore the right hand side of the above inequality is an increasing function of γ_g. Hence we obtain

$$\theta_1 < \frac{\theta_1/(k-1)^2}{q_1q_2(2\theta_2+\theta_1)}\left\{2(k-1)^2 + \frac{\theta_1(k-1)^2}{2\theta_2+\theta_1}\right\} = \frac{\theta_1}{q_1q_2(2\theta_2+\theta_1)}\left\{2+\frac{\theta_1}{2\theta_2+\theta_1}\right\}.$$

Thus $(2\theta_2+\theta_1)^2 < \frac{3\theta_1+4\theta_2}{q_1q_2}$. Then we derive

$$(2\theta_2+\theta_1-\frac{1}{q_1q_2})^2 < \frac{1}{(q_1q_2)^2}+\frac{\theta_1}{q_1q_2}.$$

Thus we get either $2\theta_2+\theta_1 < \frac{1}{q_1q_2}$ or $2\theta_2+\theta_1-\frac{1}{q_1q_2} < \sqrt{\frac{1}{(q_1q_2)^2}+\frac{\theta_1}{q_1q_2}}$ giving (3.5). Further from (3.14), we have

$$d_1 < \frac{\theta_1(\gamma_g-\gamma_h)^2}{q_1(2\theta_2(k-1)+\theta_1(\gamma_g+\gamma_h))} < \frac{\theta_1(k-1)}{q_1(2\theta_2+\theta_1)}.$$

As in Case I, we have $d_2 < \frac{4(k-1)}{q_2}$. Thus (3.6) follows. □

Let θ_1, θ_2 be as in as the statement of Lemma 3.1.

Corollary 3.2. *We have*

$$\theta_1 < \frac{3}{q_1q_2},\ \theta_1+\theta_2 < \theta_1+2\theta_2 < \frac{3}{q_1q_2}. \tag{3.18}$$

Proof. Since $\theta_2 > 0$, we see from (3.5) that either $\theta_1 < \frac{1}{q_1q_2}$ or $(\theta_1-\frac{1}{q_1q_2})^2 < \frac{1}{(q_1q_2)^2}+\frac{\theta_1}{q_1q_2}$ giving $\theta_1 < \frac{3}{q_1q_2}$. Hence we get from (3.5) that

$$\theta_1+2\theta_2 < \frac{1}{q_1q_2}+\sqrt{\frac{1}{(q_1q_2)^2}+\frac{\theta_1}{q_1q_2}} < \frac{3}{q_1q_2}.$$

Thus (3.18) is valid. □

Lemma 3.3. *Let $b_i = b_j, b_g = b_h$ and $(d_1, d_2) \neq (\eta, \frac{d}{\eta})$ be a partition of d. Suppose that (i, j) and (g, h) correspond to the partitions (d_1, d_2) and (d_2, d_1), respectively. Then*

$$d_1 < \eta(k-1)^2,\ d_2 < \eta(k-1)^2. \tag{3.19}$$

Proof. We write

$$y_i - y_j = d_1r_1,\ y_i + y_j = d_2r_2,\ y_g - y_h = d_2s_2,\ y_g + y_h = d_1s_1.$$

with

$$b_ir_1r_2 = \gamma_i - \gamma_j, b_gs_1s_2 = \gamma_g - \gamma_h. \tag{3.20}$$

Then as in the proof of Lemma 3.1, we get (3.7) and (3.8). If both $b_ir_1^2 - b_gs_1^2 \neq 0$ and $b_ir_2^2 - b_gs_2^2 \neq 0$, we obtain $\max(d_1, d_2) < \eta\ \max(b_ir_1^2, b_gs_1^2,\ b_ir_2^2, b_gs_2^2) \leq \eta(k-1)^2$ by (3.20). Thus we may assume that either $b_ir_1^2 - b_gs_1^2 = 0$ or $b_ir_2^2 - b_gs_2^2 = 0$. Note that $b_ir_1^2 - b_gs_1^2 = b_ir_2^2 - b_gs_2^2 = 0$ is not possible. Suppose

$b_ir_1^2-b_gs_1^2=b_ir_2^2-b_gs_2^2=0$. Then $b_i=b_g, r_1=s_1, r_2=s_2$ implying $y_i=y_g, y_j=y_h$. Hence we get $\gamma_i=\gamma_g, \gamma_j=\gamma_h$ from (2.2) implying $(i,j)=(g,h)$ which is a contradiction. Now we consider the case $b_ir_1^2-b_gs_1^2=0$ and the proof for the other is similar. From $b_ir_2^2-b_gs_2^2\neq 0$ and (3.7), we obtain $2(\gamma_i+\gamma_j-\gamma_g-\gamma_h)d_1=(b_ir_2^2-b_gs_2^2)d_2$ implying $d_1\Big|\eta(b_ir_2^2-b_gs_2^2)$ and $d_2\Big|2\eta(\gamma_i+\gamma_j-\gamma_g-\gamma_h)$. Hence by (3.20), $d_1<\eta(k-1)^2, d_2<2\eta(k-1+k-2-1)\le\eta(k-1)^2$ implying (3.19). □

For two pairs $(a,b),(c,d)$ with positive rationals a,b,c,d, we write $(a,b)\ge(c,d)$ if $a\ge c,\ b\ge d$.

Lemma 3.4. *Let (d_1,d_2) be a partition of d. Suppose that there is a set $\mathfrak{G}$ of at least z_0 distinct pairs corresponding to the partition (d_1,d_2) such that $V(i,j,g,h,d_1,d_2)$ is non-degenerate for any (i,j) and (g,h) in $\mathfrak{G}$. Then* (3.5), (3.6) *and* (3.18) *hold with $(q_1,q_2)\ge(Q_1,Q_2)$ where (Q_1,Q_2) is given by the following table.*

z_0	d *odd*	$2\|\|d$	$4\|\|d$	$8\|d$
2	$(1,1)$	$(2,1)$	$(\frac12,\frac12)$	$(1,\frac12)$ *if* $2\|\|d_1$, $(\frac12,1)$ *if* $2\|\|d_2$
3	$(2,2)$	$(4,4)$ *or* $(8,2)$	$(2,2)$	$(2,2)$
5	$(4,4)$	$(8,4)$	$(2,8)$ *or* $(8,2)$	$(2,8)$ *if* $2\|\|d_1$, $(8,2)$ *if* $2\|\|d_2$

Table 1

For example, $(Q_1,Q_2)=(1,1)$ if $z_0=2, d$ odd and $(Q_1,Q_2)=(2,2)$ if $z_0=3, 4||d$. If there exists a non-degenerate double pair $V(i,j,g,h,d_1,d_2)$, then we can apply Lemma 3.4 with $z_0=2$.

Proof. For any pair $(i,j)\in\mathfrak{G}$, we write

$$y_i-y_j=r_1(i,j)d_1 \quad\text{and}\quad y_i+y_j=r_2(i,j)d_2 \tag{3.21}$$

where $r_1=r_1(i,j)$ and $r_2=r_2(i,j)$ are integers.

Let d be odd. Then $r_1\equiv r_2(\text{mod } 2)$ for any pair (i,j) by (3.21) and we shall use it in this paragraph without reference. We observe that $q_1\ge 1, q_2\ge 1$ by (3.8), (3.4) and the assertion follows for $z_0=2$. Let $z_0=3$. If there are two distinct pairs (i,j) with b_ir_1 even, then $q_1\ge 2, q_2\ge 2$ by (3.8). Thus we may assume that there is at most one pair (i,j) for which b_ir_1 is even. Therefore, for the remaining two pairs, we see that both b_ir_1's are odd and the assertion follows again by (3.8). Let $z_0=5$. We may suppose that there is at most one (i,j) for which r_1 is even otherwise the result follows from (3.8). Now we consider remaining four pairs (i,j) for which $r_1^2\equiv 1(\text{mod } 4)$. Out of these pairs, there are (i_1,j_1) and (i_2,j_2) such that $b_{i_1}\equiv b_{i_2}(\text{mod } 4)$ since b's are square free. Now the assertion follows from (3.8).

Let d be even. We observe that

$$8|(y_i^2-y_j^2) \text{ and } \gcd(y_i-y_j, y_i+y_j)=2 \tag{3.22}$$

for any pair (i,j). Let $2||d$. Then d_1 is odd and d_2 is even implying r_1 is even by (3.22). Further from (3.22), we have either $4|r_1, 2\nmid r_2$ or $2||r_1, 2|r_2$. Therefore $(q_1,q_2)\ge(2,1)$ by (3.8) since r_1 is even and the assertion follows for $z_0=2$. Let $z_0=3$. Then there are two pairs (i_1,j_1) and (i_2,j_2) such that $r_2(i_1,j_1)\equiv r_2(i_2,j_2)(\text{mod } 2)$. Assume that r_2 is odd. Then $4|r_1$ which implies $8|q_1$ and $2|q_2$ by (3.8). Now we suppose that r_2 is even. Then $2||r_1$. We write $r_1=2r_1'$ and

$$b_{i_1}r_1^2(i_1,j_1)-b_{i_2}r_1^2(i_2,j_2)=4(b_{i_1}r_1'^2(i_1,j_1)-b_{i_2}r_1'^2(i_2,j_2))\equiv 0(\text{mod } 8).$$

Hence $4|q_1$, $4|q_2$ by (3.8). Let $z_0 = 5$. We choose three pairs (i, j) for which all b_i's $\equiv 1 (\text{mod } 4)$ or all b_i's $\equiv 3 (\text{mod } 4)$. Out of these, we choose two pairs both of which satisfy either $4|r_1, 2 \nmid r_2$ or $2||r_1, 2|r_2$. Now we argue as above and use $b_{i_1} \equiv b_{i_2} (\text{mod } 4)$ to get the result.

Let $4||d$. Then both d_1 and d_2 are even. From (3.22), we have either $2|r_1, 2 \nmid r_2$ or $2 \nmid r_1, 2|r_2$. Since $(q_1, q_2) \geq (\frac{1}{2}, \frac{1}{2})$ by (3.8), the the assertion follows for $z_0 = 2$. Let $z_0 = 3$. Then there are two pairs (i_1, j_1) and (i_2, j_2) such that $r_1(i_1, j_1) \equiv r_1(i_2, j_2) (\text{mod } 2)$ and $r_2(i_1, j_1) \equiv r_2(i_2, j_2) (\text{mod } 2)$. Since $b_i \equiv n (\text{mod } 4)$ for each i, we get from (3.8) and (3.4) that $2|q_1$ and $2|q_2$. Thus $(q_1, q_2) \geq (2, 2)$. Let $z_0 = 5$. Then we get 3 pairs (i, j) for which $2|r_1(i, j), 2 \nmid r_2(i, j)$ or 3 pairs (i, j) for which $2 \nmid r_1(i, j), 2|r_2(i, j)$. Assume the first case. Then there are 2 pairs (i_1, j_1) and (i_2, j_2) such that $r_1(i_1, j_1) \equiv r_1(i_2, j_2) (\text{mod } 4)$. This, with $b_i \equiv n (\text{mod } 4)$ and (3.4), implies that $16|q_1 d_2$ and $4|q_2 d_1$. Hence $(q_1, q_2) \geq (8, 2)$. In the latter case, we get $(q_1, q_2) \geq (2, 8)$ similarly.

Let $8|d$. Then we have from (3.21) and (3.22) that either $2||d_1$ implying all r_1's are odd, or $2||d_2$ implying all r_2's are odd. Also $b_i \equiv n (\text{mod } 8)$ for all i. We prove the result for $2||d_1$ and the proof for the other case is similar. From (3.7), we derive

$$2(\gamma_{i_1} + \gamma_{j_1} - \gamma_{i_2} - \gamma_{j_2}) \frac{d_1}{2} \frac{d_2}{2} = (b_{i_1} r_1^2 - b_{i_2} s_1^2) \left(\frac{d_1}{2}\right)^2 + (b_{i_1} r_2^2 - b_{i_2} s_2^2) \left(\frac{d_2}{2}\right)^2 \tag{3.23}$$

where $r_1 = r_1(i_1, j_1), s_1 = r_1(i_2, j_2), r_2 = r_2(i_1, j_1)$ and $s_2 = r_2(i_2, j_2)$. Noting that $4d_2 | d_2^2$ and taking modulo d_2, we get $(q_1, q_2) \geq (1, \frac{1}{2})$ implying the assertion for $z_0 = 2$. Let $z_0 = 3$. Then there are 2 pairs (i_1, j_1) and (i_2, j_2) such that $r_2(i_1, j_1) \equiv r_2(i_2, j_2) (\text{mod } 2)$. Using this and (3.4), we get $4|q_2 d_1$. Further from $b_i r_1 r_2 = \gamma_i - \gamma_j$, we see that $\gamma_{i_1} - \gamma_{j_1} \equiv \gamma_{i_2} - \gamma_{j_2} (\text{mod } 2)$ implying $\gamma_{i_1} + \gamma_{j_1} \equiv \gamma_{i_2} + \gamma_{j_2} (\text{mod } 2)$. Now we see from (3.23) that $4\frac{d_2}{2} | q_1 d_2$. Thus $(q_1, q_2) \geq (2, 2)$. Let $z_0 = 5$. We see that $b_i \equiv n$ or $n + 8$ modulo 16 so that $b_i r_2^2 (\text{mod } 16)$ is equal to 0 if $4|r_2$, $4n$ if $2||r_2$ and $n, n + 8$ if $2 \nmid r_2$. Now we can find 2 pairs (i_1, j_1) and (i_2, j_2) such that $b_{i_1} r_2^2(i_1, j_1) \equiv b_{i_2} r_2^2(i_2, j_2) (\text{mod } 16)$. This gives $16|q_2 d_1$ by (3.4). Further again $2|(\gamma_{i_1} + \gamma_{j_1} - \gamma_{i_2} - \gamma_{j_2})$ and hence $4\frac{d_2}{2} | q_1 d_2$ from (3.23). Therefore $(q_1, q_2) \geq (2, 8)$. $\square$

Lemma 3.5. (*i*) *Assume that*

$$n + \gamma_t d > \eta^2 \gamma_t^2. \tag{3.24}$$

Then for any pair (i, j) with $b_i = b_j$, the partition $(d\eta^{-1}, \eta)$ is not possible.
(*ii*) *Let $d = d' d''$ with $\gcd(d', d'') = 1$. Then for any pair (i, j) with $B_i = B_j \geq d'$, $i, j \in T_1$, the partition $(d''\eta^{-1}, \eta)$ is not possible. In particular, the partition $(d\eta^{-1}, \eta)$ is not possible.*

Proof. (i) Suppose the pair (i, j) with $b_i = b_j$ correspond to the partition $(d\eta^{-1}, \eta)$. From $\frac{n+\gamma_i d}{n+\gamma_t d} > \frac{\gamma_i}{\gamma_t}$ and (3.24), we get $n + \gamma_i d > \eta^2 \gamma_i \gamma_t$. Then from (2.8), we have

$$\gamma_i - \gamma_j \geq \frac{b_i(y_i + y_j)}{\eta} \geq \frac{(b_i y_i^2)^{\frac{1}{2}} + (b_j y_j^2)^{\frac{1}{2}}}{\eta} > \frac{\eta(\sqrt{\gamma_i \gamma_t} + \sqrt{\gamma_j \gamma_t})}{\eta} \geq \gamma_i + \gamma_j,$$

a contradiction.
(ii) Suppose the pair (i, j) with $B_i = B_j \geq d'$ correspond to the partition $(d''\eta^{-1}, \eta)$. As in (2.8), we have

$$\gamma_i - \gamma_j \geq (\gamma_i - \gamma_j) \frac{d'}{B_i} \geq \frac{Y_i + Y_j}{\eta} > \frac{2k}{2}$$

since $Y_i \geq Y_j > k$. This is a contradiction. The latter assertion follows by taking $d' = 1, d'' = d$. $\square$

Lemma 3.6. *(i) Assume* (3.24)*. Let $1\le i_0\le t$ and $\nu(b_{i_0})=\mu$. Let (d_1,d_2) be any partition of d. Then the number of pairs (i,j) with $b_i=b_j=b_{i_0}, i>j$ corresponding to (d_1,d_2) is at most $[\frac{\mu}{2}]$.*
(ii) Let $d=d^{'}d^{''}$ with $\gcd(d^{'},d^{''})=1$. Let $i_0\in T_1$, $B_{i_0}\ge d^{'}$ and $\nu(B_{i_0})=\mu$. Let (d_1,d_2) be any partition of $d^{''}$. Then the number of pairs (i,j) with $B_i=B_j=B_{i_0}, i>j$ corresponding to (d_1,d_2) is at most $[\frac{\mu}{2}]$.

Proof. (i) Suppose there are $\mu'=[\frac{\mu}{2}]+1$ pairs (i_l,j_l) with $i_l>j_l, 0\le l<\mu'$ and $b_{i_l}=b_{j_l}=b_{i_0}$ corresponding to (d_1,d_2). We consider the sets $I=\{i_l|0\le l<\mu'\}$ and $J=\{j_l|0\le l<\mu'\}$. If $|I|<\mu'$ or $|J|<\mu'$ or $I\cap J\ne\phi$, then there are $l\ne m$ such that

$$d_1|(y_{j_l}-y_{j_m}),\ d_2|(y_{j_l}-y_{j_m}) \text{ if } i_l=i_m$$
$$d_1|(y_{i_l}-y_{i_m}),\ d_2|(y_{i_l}-y_{i_m}) \text{ if } j_l=j_m$$
$$d_1|(y_{j_l}-y_{i_m}),\ d_2|(y_{j_l}-y_{i_m}) \text{ if } i_l=j_m.$$

We exclude the first possibility and proofs for the others are similar. Without loss of generality, we may assume that $j_l>j_m$. Then $\mathrm{lcm}(d_1,d_2)\big|(y_{j_l}-y_{j_m})$ so that the pair (j_l,j_m) correspond to the partition $(d\eta^{-1},\eta)$. This is not possible by Lemma 3.5 (i). Thus $|I|=\mu'$, $|J|=\mu'$ and $I\cap J=\phi$. Now we see that $|I\cup J|=|I|+|J|=2\mu'>\mu$ and $b_i=b_{i_0}$ for every $i\in I\cup J$. This contradicts $\nu(b_{i_0})=\mu$.
(ii) The proof is similar to that of (i) and we use Lemma 3.5 (ii). □

As a corollary, we have

Corollary 3.7. *(i) Assume* (3.24)*. For $1\le i\le t$, we have $\nu(b_i)\le 2^{\omega(d)-\theta}$.*
(ii) Let $d=d^{'}d^{''}$ with $\gcd(d^{'},d^{''})=1$. For $B_i\ge d^{'}$, we have $\nu(B_i)\le 2^{\omega(d^{''})-\theta_1}$. In particular, $\nu(B_i)\le 2^{\omega(d)-\theta}$.

Proof. (i) Let $\nu(b_i)=\mu$. Then there are $\frac{\mu(\mu-1)}{2}$ pairs (g,h) with $g>h$ and $b_g=b_h=b_i$. Since there are at most $2^{\omega(d)-\theta}-1$ permissible partitions of d, we see from Lemma 3.6 (i) that $\frac{\mu(\mu-1)}{2}\le\frac{\mu}{2}(2^{\omega(d)-\theta}-1)$. Hence the assertion follows.
(ii) The proof of the assertion (ii) is similar and we use Lemma 3.6 (ii). □

Corollary 3.8. *Let $T_{r+1}=\{i\in T_1: B_i\ge \mathfrak{q}_1\mathfrak{q}_2\cdots\mathfrak{q}_r\}$ and $s_{r+1}=|\{B_i: i\in T_{r+1}\}|$. Then*

$$s_{r+1}\ge\frac{|T_1|}{2^{\omega(d)-r-\theta}}-\sum_{\mu=1}^{r-1}2^{r-\mu}\lambda_\mu-2\lambda_r$$

where λ's are as defined in (2.10)*.*

Proof. We apply Corollary 3.7 (ii) with $d'=\mathfrak{q}_1\mathfrak{q}_2\cdots\mathfrak{q}_\mu$ to derive that $\nu(B_i)\le 2^{\omega(d)-\mu-\theta}$ for $B_i\ge\mathfrak{q}_1\mathfrak{q}_2\cdots\mathfrak{q}_\mu$, $\mu\ge1$ since $\theta_1\ge\theta$. Therefore

$$|T_{r+1}|\ge|T_1|-2^{\omega(d)-\theta}\lambda_1-2^{\omega(d)-1-\theta}(\lambda_2-\lambda_1)-\cdots-2^{\omega(d)-r+1-\theta}(\lambda_r-\lambda_{r-1}).$$

Since $\nu(B_i)\le 2^{\omega(d)-r-\theta}$ for $i\in T_{r+1}$, we have $s_{r+1}\ge\frac{|T_{r+1}|}{2^{\omega(d)-r-\theta}}$ and the assertion follows. □

Lemma 3.9. *Assume* (3.24)*. There exists a set Ω of at least*

$$t-|R|+\sum_{\substack{\mu>1\\ \mu\text{ odd}}}r_\mu\ge t-|R|$$

pairs (i, j) having Property ND.

Proof. We have

$$t = \sum_{\mu} \mu r_\mu \quad \text{and} \quad |R| = \sum_{\mu} r_\mu.$$

Each $b_{i_0} \in R_\mu$ gives rise to $\frac{\mu(\mu-1)}{2}$ pairs (i, j) with $i > j$ such that $b_i = b_j = b_{i_0}$ and each pair corresponds to a partition of d. By Lemma 3.6, we know that there are at most $[\frac{\mu}{2}]$ pairs corresponding to any partition of d. For each $1 \le j \le [\frac{\mu}{2}] = \mu_1$, let v_j be the number of partitions of d for which there are j pairs out of the ones given by $b_{i_0} \in R_\mu$ corresponding to that partition. Then

$$\frac{\mu(\mu-1)}{2} = \sum_{j=1}^{\mu_1} j v_j. \tag{3.25}$$

For each partition having j pairs with $v_j > 0$, we remove $j-1$ pairs. Then we remove in all $\sum_{j=1}^{\mu_1}(j-1)v_j$ pairs. Rewriting (3.25) as

$$\frac{\mu(\mu-1)}{2} = \mu_1 \sum_{j=1}^{\mu_1} v_j - \sum_{j=1}^{\mu_1} (\mu_1 - j) v_j,$$

we see that we are left with at least

$$\sum_{j=1}^{\mu_1} v_j = \frac{\mu(\mu-1)}{2\mu_1} + \sum_{j=1}^{\mu_1}(1 - \frac{j}{\mu_1}) v_j \ge \frac{\mu(\mu-1)}{2\mu_1} = \begin{cases} \mu - 1 & \text{if } \mu \text{ is even} \\ \mu & \text{if } \mu \text{ is odd} \end{cases}$$

pairs. Let Ω be the union of all such pairs taken over all $b_{i_0} \in R_\mu$ and for all $\mu \ge 2$. Since $|R_\mu| = r_\mu$, we have

$$|\Omega| \ge \sum_{\mu \text{ even}} (\mu - 1) r_\mu + \sum_{\substack{\mu > 1 \\ \mu \text{ odd}}} \mu r_\mu = t - |R| + \sum_{\substack{\mu > 1 \\ \mu \text{ odd}}} r_\mu.$$

Further we see from the construction of the set Ω that Ω satisfy *Property ND.* $\square$

Corollary 3.10. *Assume* (3.24). *Let z be a positive integer and $\mathfrak{h}(z) = (z-1)(2^{\omega(d)-\theta} - 1) + 1$. Let $z_0 \in \{2, 3, 5\}$. Suppose that $t - |R| \ge \mathfrak{h}(z_0)$. Then there exists a partition (d_1, d_2) of d such that* (3.5), (3.6) *and* (3.18) *hold with $(q_1, q_2) \ge (Q_1, Q_2)$ where (Q_1, Q_2) is given by Table 1.*

Proof. By Lemma 3.9, there exists a set Ω with at least $\mathfrak{h}(z_0)$ pairs satisfying *Property ND.* Since there are at most $2^{\omega(d)-\theta} - 1$ permissible partitions of d by Lemma 3.5 (i), we can find a partition (d_1, d_2) of d and a subset $\mathfrak{G} \subset \Omega$ of at least z_0 pairs corresponding to (d_1, d_2). Now the result follows by Lemma 3.4. $\square$

Corollary 3.11. *Assume* (3.24). *Suppose that $t - |R| \ge 2^{\omega(d)-\theta-1} + 1$. Then there exists a partition (d_1, d_2) of d such that* (3.19) *holds.*

Proof. By Lemma 3.9, there exists a set Ω with at least $2^{\omega(d)-\theta-1} + 1$ pairs (i, j) satisfying *Property ND.* We may assume that for each partition (d_1, d_2) of d, there is at most 1 pair corresponding to (d_1, d_2) otherwise the assertion follows by $z_0 = 2$ in Lemma 3.4. We see that there are $2^{\omega(d)-\theta-1} - 1$ partitions (d_1, d_2) with $d_1 > d_2$, $2^{\omega(d)-\theta-1} - 1$ partitions (d_1, d_2) with $\eta < d_1 < d_2$ and the partition $(\eta, d\eta^{-1})$. Since there are at least $2^{\omega(d)-\theta-1} + 1$ pairs, we can find two pairs (i, j) and (g, h) corresponding to the partitions (d_1, d_2) and (d_2, d_1), respectively. Now the assertion follows by Lemma 3.3. $\square$

Lemma 3.12. *Assume* (3.24).
(i) Let $|S_1|\le|T_1|-\mathfrak{h}(3)$*. Then* (3.18) *is valid with*

$$q_1q_2\ge\begin{cases}144\rho^{-1} & \text{if } 2\nmid d\\ 16 & \text{if } 2||d\\ 4 & \text{if } 4|d.\end{cases}\tag{3.26}$$

(ii) Let d be even and $|S_1|\le|T_1|-\mathfrak{h}(5)$*. Then* (3.18) *is valid with*

$$q_1q_2\ge\begin{cases}144\rho^{-1} & \text{if } 2||d\\ 36 & \text{if } 4|d \text{ and } 3\nmid d\\ 16 & \text{if } 4|d \text{ and } 3|d.\end{cases}\tag{3.27}$$

Proof. Let $B_i=B_j$ with $i>j$ and $i,j\in T_1$. Then there is a partition (d_1,d_2) of d such that $Y_i-Y_j=d_1r_1'$, $Y_i+Y_j=d_2r_2'$ with r_1',r_2' even, $24\rho^{-1}|r_1'r_2'$ if d is odd and r_1' even, $12\rho^{-1}|r_1'r_2'$ if $2||d$ and $3\rho^{-1}|r_1'r_2'$ if $4|d$. Since $B_iY_i^2=b_iy_i^2$ and b_i is squarefree, we see that $p|b_i$ if and only if $p|B_i$ with $\mathrm{ord}_p(B_i)$ odd. Therefore $b_i=b_j$ implying $b^2=\frac{B_i}{b_i}=\frac{B_j}{b_j}$ and $y_i=bY_i,y_j=bY_j$. Hence

$$y_i-y_j=d_1br_1'=d_1r_1(i,j)=d_1r_1,\ y_i+y_j=d_2br_2'=d_2r_2(i,j)=d_2r_2$$

with $r_1=br_1',r_2=br_2'$ even, $24\rho^{-1}|r_1r_2$ if d is odd; r_1 even, $12\rho^{-1}|r_1r_2$ if $2||d$ and $3\rho^{-1}|r_1r_2$ if $4|d$. Let $z\in\{3,5\}$ and $|S_1|\le|T_1|-\mathfrak{h}(z)$. We argue as in Lemma 3.9 and Corollary 3.10 with t and $|R|$ replaced by $|T_1|$ and $|S_1|$. There exists a partition (d_1,d_2) of d and z pairs corresponding to (d_1,d_2) such that $V(i,j,g,h,d_1,d_2)$ is non-degenerate for any two such distinct pairs (i,j) and (g,h). Let $z=3$. By Lemma 3.4 with $z_0=3$, we may suppose that d is odd. Let $3\nmid d$. Then we can find two distinct pairs (i_1,j_1) and (i_2,j_2) both of which satisfy either $3|r_1(i_1,j_1)$, $3|r_1(i_2,j_2)$ or $3|r_2(i_1,j_1),3|r_2(i_2,j_2)$. Now (3.26) follows from (3.8) and (3.4) since r_1,r_2 are even. Assume that $3|d$. Let $3|d_1$. Then we can find two distinct pairs (i_1,j_1) and (i_2,j_2) both of which satisfy either $3|r_1(i_1,j_1)$, $3|r_1(i_2,j_2)$ or $3\nmid r_1(i_1,j_1)$, $3\nmid r_1(i_2,j_2)$. Since $b_i\equiv n(\text{mod }3)$ and $r^2\equiv 1(\text{mod }3)$ for $3\nmid r$, the assertion follows from (3.8) and (3.4) since r_1,r_2 are even. The same assertion hold for $3|d_2$ in which case r_1 is replaced by r_2. This proves (3.26) and we turn to the proof of (3.27). Let d be even and $z=5$. Let $3\nmid d$. Out of these five pairs, we can find three distinct pairs (i,j) for which either $r_1(i,j)$'s are all divisible by 3 or $r_2(i,j)$'s are all divisible by 3. As in the proof of Lemma 3.4 with d even and $z_0=3$, we find two distinct pairs (i_1,j_1) and (i_2,j_2) such that $16|q_1q_2$ if $2||d$ and $4|q_1q_2$ if $4|d$. Further $9|q_1q_2$ since either $r_1(i,j)$'s are all divisible by 3 or $r_2(i,j)$'s are all divisible by 3 and hence the assertion. Assume now that $3|d$. By Lemma 3.4 with $z_0=5$, we may suppose that $2||d$. Let $3|d_1$. Then we can find three pairs (i,j) for which either 3 divides all $r_1(i,j)$'s or 3 does not divide any $r_1(i,j)$. Then for any two such pairs (i_1,j_1) and (i_2,j_2), we have $3|(b_{i_1}r_1^2(i_1,j_1)-b_{i_2}r_1^2(i_2,j_2))$. Therefore by the proof of Lemma 3.4 with d even and $z_0=3$, we get $3\cdot 16|q_1q_2$. The other case $3|d_2$ is similar. □

4. Lower bound for $n+(k-1)d$

We observe that $|S_1|\ge\frac{|T_1|}{2^{\omega(d)-\theta}}$ and $n+(k-1)d\ge|S_1|k^2$. We give lower bound for $|T_1|$. We have

Lemma 4.1. *Let* $k\ge 4$*. Then*

$$|T_1|>t-\frac{(k-1)\log\,(k-1)-\sum_{p|d,p<k}\max\left(0,\frac{(k-1-p)\log p}{p-1}-\log(k-2)\right)}{\log\,(n+(k-1)d)}-\pi_d(k)-1.\tag{4.1}$$

Proof. The proof depends on an idea of Sylvester and Erdős and it is similar to [SaSh03a, Lemma 3]. Since $|T_1| = t - |T|$, we may assume that $|T| > \pi_d(k)$. For a prime q with $q \le k$ and $q \nmid d$, let i_q be a term such that $\mathrm{ord}_q(B_{i_q})$ is maximal. Let $T' = T \setminus \{i_q : q \le k, q \nmid d\}$. Thus $|T'| \ge |T| - \pi_d(k)$. Let $i \in T'$. Then $n + \gamma_i d = B_i$ and $\mathrm{ord}_q(n + \gamma_i d) \le \mathrm{ord}_q(\gamma_i - \gamma_{i_q})$ since $\gcd(n, d) = 1$. Therefore

$$\mathrm{ord}_q(\prod_{i\in T'}(n+\gamma_i d)) \le \mathrm{ord}_q((\gamma_{i_q})!(k-1-\gamma_{i_q})!) \le \mathrm{ord}_q(k-1)!.$$

This, with $n + id \ge \frac{i}{k-1}(n + (k-1)d)$ for $i > 0$, gives

$$(|T'|-1)!\left(\frac{n+(k-1)d}{k-1}\right)^{|T'|-1} < \prod_{i\in T'}(n+\gamma_i d) \le (k-1)!\psi^{-1}$$

where $\psi = \prod_{q|d} q^{\mathrm{ord}_q(k-1)!}$. Therefore

$$\begin{aligned}&(|T| - \pi_d(k) - 1)\log(n + (k-1)d)\\ <&(|T'|-1)\log(k-1) + \log((k-1)\cdots|T'|) - \log\psi \le (k-1)\log(k-1) - \log\psi.\end{aligned}$$

Now the assertion (4.1) follows from Lemma 5.1 (iv). □

The following result is an immediate consequence of Laishram and Shorey [LaSh06, Theorem 1].

Lemma 4.2. *Let $n \ge 1, d > 2$ and $k \ge 5$. Then*

$$P(n(n+d)\cdots(n+(k-1)d)) > 2k \tag{4.2}$$

unless $(n, d, k) = (1, 3, 10)$.

Lemma 4.3. *Let $t = k$. Then we have*

$$|T_1| > \alpha k \text{ for } k \ge K_\alpha \tag{4.3}$$

where α and K_α are given by

α	0.3	0.35	0.4	0.42
K_α	101	203	710	1639

Proof. Let $k \ge K_\alpha$. Thus $k \ge 101$. From Lemma 4.2, we have $n + (k-1)d > 4k^2$. We see from (4.1) that

$$|T_1| + \pi_d(k) > k - 1 - \frac{(k-1)\log k}{2\log 2k} = \frac{k}{2} + \frac{1}{2}\left\{\frac{(k-1)\log 2}{\log 2k} - 1\right\} > \frac{k}{2}.$$

Therefore $n + (k-1)d > (\frac{k}{2}\log\frac{k}{2})^2$ by Lemma 5.1 (ii).

For $0 < \beta < 1$, let

$$n + (k-1)d > (\beta k \log \beta k)^2. \tag{4.4}$$

We may assume that $\beta \ge \frac{1}{2}$. Put $X_\beta = X_\beta(k) = \beta\log(\beta k)$. Then $\log(n + (k-1)d) > 2\log X_\beta + 2\log k$. From (4.1), we see that

$$\begin{aligned}|T_1| + \pi_d(k) >& k - 1 - \frac{(k-1)\log k}{2\log X_\beta + 2\log k} = \frac{k}{2}\left(1-\frac{1}{k}\right)\left(1+\frac{\log X_\beta}{\log X_\beta + \log k}\right)\\ =&\frac{k}{2}\left(1-\frac{1}{k}\right)\left(1+\frac{1}{1+\frac{\log k}{\log X_\beta}}\right) =: g_\beta(k)k =: g_\beta k.\end{aligned} \tag{4.5}$$

By using $\pi_d(k)\le\pi(k)$ and Lemma 5.1 (i), we get from (4.5) that

$$|T_1|>g_\beta k-\frac{k}{\log k}\left(1+\frac{1.2762}{\log k}\right). \tag{4.6}$$

Let $\beta=\frac{1}{2}$. We observe that

$$\begin{aligned}&\frac{14}{13}\log k-\left(1+\frac{\log k}{\log X_\beta}\right)\left(1+\frac{1.2762}{\log k}\right)\\ =&\left(\frac{14}{13}-\frac{1}{\log X_\beta}\right)\log k-\left(\frac{1.2762}{\log k}+\frac{1.2762}{\log X_\beta}\right)-1\end{aligned}$$

is an increasing function of k and it is positive at $k=2500$. Therefore

$$\frac{1}{1+\frac{\log k}{\log X_\beta}}>\frac{13}{14}\frac{1}{\log k}\left(1+\frac{1.2762}{\log k}\right)\text{ for }k\ge 2500$$

which, together with (4.6) and (4.5), implies

$$\frac{|T_1|}{k}>\frac{1}{2}-\frac{1}{2k}-\frac{1}{28\log k}\left(1+\frac{1.2762}{\log k}\right)\left(15+\frac{13}{k}\right)>0.42\text{ for }k\ge 2500$$

since the middle expression is an increasing function of k. Thus we may suppose that $k<2500$. From (4.5), we get $|T_1|+\pi_d(k)>g_{\frac{1}{2}}k=:\beta_1 k$. Then (4.4) is valid with β replaced by β_1 and we get from (4.5) that $|T_1|+\pi_d(k)>g_{\beta_1}k=:\beta_2 k$. We iterate this process with β replaced by β_2 to get $g_{\beta_2}=:\beta_3$ and further with β_3 to get $|T_1|+\pi_d(k)>g_{\beta_3}k=:\beta_4 k$. Finally we see that $|T_1|>\beta_4 k-\pi(k)\ge\alpha k$ for $k\ge K_\alpha$. □

Lemma 4.4. *Let $S\subseteq\{B_i:1\le i\le t\}$. Let $h\ge 1$ and $P_1<P_2<\cdots<P_h$ be a subset of odd primes dividing d. For $|S|>\left(\frac{P_1-1}{2}\right)\cdots\left(\frac{P_h-1}{2}\right)$, we have*

$$\max_{B_i\in S}B_i\ge\begin{cases}\frac{3}{4}2^{h+\delta}|S| & \text{if }3\nmid d\\ \frac{9}{8}2^{h+\delta}|S| & \text{if }3|d.\end{cases} \tag{4.7}$$

Proof. The assertion (4.7) for $3\nmid d$ is [Lai06, Corollary 2] with A_i replaced by B_i and $s=|S|$. Let $3|d$. As in [Lai06, Corollary 2], let $Q_h\ge 1$ and $1\le f\le\frac{P_h-1}{2}$ be integers such that $(f-1)\left(\frac{P_1-1}{2}\right)\cdots\left(\frac{P_{h-1}-1}{2}\right)<|S|-Q_h\left(\frac{P_1-1}{2}\right)\cdots\left(\frac{P_h-1}{2}\right)\le f\left(\frac{P_1-1}{2}\right)\cdots\left(\frac{P_{t-1}-1}{2}\right)$. Then we continue the proof as in [Lai06, Corollary 2] to get

$$\max_{B_i\in S}B_i\ge 2^\delta Q_hP_1P_2\cdots P_h+2^\delta(f-1)P_1P_2\cdots P_{h-1}.$$

Since $P_1=3$, it suffices to show

$$Q_hP_2\cdots P_h+(f-1)P_2\cdots P_{h-1}\ge\frac{3}{4}\left\{Q_h(P_2-1)\cdots(P_h-1)+2f(P_2-1)\cdots(P_{h-1}-1)\right\}$$

for getting the the assertion (4.7). For $h=2$, we see from

$$\frac{1}{4}Q_h(P_2+3)-1-\frac{f}{2}\ge\frac{1}{4}P_2-\frac{1}{4}-\frac{P_2-1}{4}=0$$

that the above inequality is valid. For $h\ge 3$, by observing that

$$Q_h(P_2-1)\cdots(P_h-1)\le Q_hP_2\cdots P_h-Q_hP_2\cdots P_{h-1},$$

$$2f(P_2-1)\cdots(P_{h-1}-1)\le 2fP_2\cdots P_{h-1}-2fP_2\cdots P_{h-2},$$

it suffices to show that

$$Q_h+\frac{3(Q_h-1)-(2f+1)}{P_h}+\frac{6f}{P_hP_{h-1}}\ge 0$$

which is true since $Q_h\ge 1$ and $1\le f\le\frac{P_h-1}{2}$. □

Corollary 4.5. *We have* $\lambda_1 < \frac{2}{3}\mathfrak{q}_1$ *if* $2 \nmid d, 3 \nmid d$ *and* $\lambda_1 < \frac{\mathfrak{q}_1}{\rho 2^\delta} + 1$ *otherwise. For* $r \geq 2$*, we have*

$$\lambda_r < \begin{cases} \frac{\mathfrak{q}_1\mathfrak{q}_2\cdots\mathfrak{q}_r}{3\cdot 2^{r-2}} & \text{if } 2 \nmid d, 3 \nmid d \\ \frac{\mathfrak{q}_1\cdots\mathfrak{q}_r}{9\cdot 2^{r-3}} & \text{if } 2 \nmid d, 3|d \\ \frac{\mathfrak{q}_1\cdots\mathfrak{q}_r}{3\cdot 2^{\delta+r-3}} & \text{if } 2|d, 3 \nmid d \\ \min(\frac{\mathfrak{q}_1\cdots\mathfrak{q}_r}{3\cdot 2^{\delta}} + 1, \frac{\mathfrak{q}_1\cdots\mathfrak{q}_r}{9\cdot 2^{r-2}}) & \text{if } 6|d. \end{cases}$$

Proof. Let $2 \nmid d$ and $3 \nmid d$. If $\lambda_r \geq \frac{\mathfrak{q}_1\cdots\mathfrak{q}_r}{3\cdot 2^{r-2}}$, then $\lambda_r > \frac{\mathfrak{q}_1-1}{2}\cdots\frac{\mathfrak{q}_r-1}{2} \geq \frac{\mathfrak{p}_1-1}{2}\cdots\frac{\mathfrak{p}_r-1}{2}$ giving $\mathfrak{q}_1\cdots\mathfrak{q}_r > \max_{B_i\in\mathcal{A}_r} B_i \geq \frac{3}{4}2^r\lambda_r$ by (4.7) with $S = \mathcal{A}_r$. This is a contradiction.

Let $2|d$ or $3|d$. Then we derive from Chinese remainder theorem that $\lambda_r < \frac{\mathfrak{q}_1\cdots\mathfrak{q}_r}{\rho 2^\delta} + 1$. Thus we may suppose that $r \geq 2$. Further we may also assume that $r \geq \delta + 1$ when $6|d$.

Let $2 \nmid d$ and $3|d$. Suppose $\lambda_r \geq \frac{\mathfrak{q}_1\cdots\mathfrak{q}_r}{9\cdot 2^{r-3}}$. Then $\mathfrak{q}_1 \geq \mathfrak{p}_1 = 3$ implying $\lambda_r > \frac{\mathfrak{q}_2-1}{2}\cdots\frac{\mathfrak{q}_r-1}{2} \geq \frac{\mathfrak{p}_1-1}{2}\frac{\mathfrak{p}_2-1}{2}\cdots\frac{\mathfrak{p}_r-1}{2}$. Therefore $\mathfrak{q}_1\cdots\mathfrak{q}_r > \frac{9}{4}2^{r-1}\lambda_r$ by (4.7) with $S = \mathcal{A}_r$. This is a contradiction.

Let $2|d$ and $3 \nmid d$. Suppose $\lambda_r \geq \frac{\mathfrak{q}_1\cdots\mathfrak{q}_r}{3\cdot 2^{\delta+r-3}}$. Then $\mathfrak{q}_r \geq 7$ since $r \geq 2$ implying $\mathfrak{q}' := \max(\mathfrak{q}_r, 2^\delta) \geq 7$ implying

$$\lambda_r \geq \frac{2^{r-1}\mathfrak{q}'}{3\cdot 2^{\delta+r-3}}\frac{\mathfrak{p}_1-1}{2}\cdots\frac{\mathfrak{p}_{r-1}-1}{2} \geq \frac{\mathfrak{q}'}{6}\frac{\mathfrak{p}_1-1}{2}\cdots\frac{\mathfrak{p}_{r-1}-1}{2} > \frac{\mathfrak{p}_1-1}{2}\cdots\frac{\mathfrak{p}_{r-1}-1}{2}.$$

Now we apply (4.7) with $S = \mathcal{A}_r$ to get a contradiction.

Let $6|d$. Suppose $\lambda_r \geq \frac{\mathfrak{q}_1\cdots\mathfrak{q}_r}{9\cdot 2^{r-2}}$. Let $2||d$ or $4||d$. Then $\lambda_r > \frac{\mathfrak{q}_2-1}{2}\cdots\frac{\mathfrak{q}_{r-1}-1}{2} \geq \frac{\mathfrak{p}_1-1}{2}\frac{\mathfrak{p}_2-1}{2}\cdots\frac{\mathfrak{p}_{r-2}-1}{2}$ since $\mathfrak{q}_1\mathfrak{q}_r \geq 9$ and $\mathfrak{p}_1 = 3$. Now we apply (4.7) with $S = \mathcal{A}_r$ to get a contradiction. Thus it remains to consider $8|d$. Then $\lambda_r > \frac{\mathfrak{q}_2-1}{2}\cdots\frac{\mathfrak{q}_{r-1}-1}{2} \geq \frac{\mathfrak{p}_1-1}{2}\frac{\mathfrak{p}_2-1}{2}\cdots\frac{\mathfrak{p}_{r-1}-1}{2}$ since

$$\lambda_r \geq \frac{2^{r-2}\mathfrak{q}_1\mathfrak{q}'}{9\cdot 2^{r-2}}\frac{\mathfrak{p}_1-1}{2}\cdots\frac{\mathfrak{p}_{r-2}-1}{2} > \frac{\mathfrak{p}_1-1}{2}\cdots\frac{\mathfrak{p}_{r-2}-1}{2}.$$

where $\mathfrak{q}' := \max(\mathfrak{q}_r, 8)$. Now we apply (4.7) with $S = \mathcal{A}_r$ to get a contradiction. □

5. Results from other sources

We now state some lemmas. We begin with some estimates from Prime Number theory.

Lemma 5.1. *We have*

(*i*) $\pi(x) \leq \frac{x}{\log x}\left(1 + \frac{1.2762}{\log x}\right)$ for $x > 1$

(*ii*) $p_i \geq i \log i$ for $i \geq 2$

(*iii*) $\prod_{p\leq x} p < 2.71851^x$ for $x > 0$

(*iv*) $\sum_{p\leq p_i} \log p > i(\log i + \log\log i - 1.076868)$ for $i \geq 2$

(*v*) $\text{ord}_p(k!) \geq \frac{k-p}{p-1} - \frac{\log(k-1)}{\log p}$ for $p < k$.

The estimates (*i*) is due to Dusart [Dus98, p.14], [Dus99] and (*ii*) is proved by Rosser and Schoenfeld [RoSc62]. For estimate (iii) is due to [Dus98, Prop 1.7], [Dus99]. The estimate (*iv*) is [Rob83, Theorem 6]. For a proof of (*iv*), see [LaSh04, Lemma 2(i)]. □

The next lemma is Stirling's formula, see Robbins [Rob55].

Lemma 5.2. *For a positive integer* ν*, we have*

$$\sqrt{2\pi\nu}\ e^{-\nu}\nu^\nu e^{\frac{1}{12\nu+1}} < \nu! < \sqrt{2\pi\nu}\ e^{-\nu}\nu^\nu e^{\frac{1}{12\nu}}.$$

The following lemma is contained in [Lai06, Lemma 8].

Lemma 5.3. *Let s_i denote the i-th squarefree positive integer. Then*

$$\prod_{i=1}^{l} s_i \ge (1.6)^l l! \quad for \quad l \ge 286. \tag{5.1}$$

Further let t_i be i-th odd squarefree positive integer. Then

$$\prod_{i=1}^{l} t_i \ge (2.4)^l l! \quad for \quad l \ge 200. \tag{5.2}$$

The next result depends on an idea of Erdős and Rigge.

Lemma 5.4. *Let $z_1 > 1$ be a real number, $h_0 > i_0 \ge 0$ be integers such that $\prod_{b_i \in R} b_i \ge z_1^{|R|-i_0}(|R|-i_0)!$ for $|R| \ge h_0$. Suppose that $t - |R| < g$ and let $g_1 = k - t + g - 1 + i_0$. For $k \ge h_0 + g_1$ and for any real number $\mathfrak{m} > 1$, we have*

$$g_1 > \frac{k \log\left(\frac{z_1 \mathfrak{n}_0}{2.71851} \prod_{p \le \mathfrak{m}} p^{\frac{2}{p^2-1}\left(1-\frac{1}{p^{\mathfrak{n}(k,p)}}\right)}\right) + (k+\frac{1}{2})\log(1-\frac{g_1}{k})}{\log(k-g_1) - 1 + \log z_1} + \frac{(0.5\ell+1)\log k - \log\left(\mathfrak{n}_1^{-1}\prod_{p\le\mathfrak{m}} p^{1.5\mathfrak{n}(k,p)}\right)}{\log(k-g_1) - 1 + \log z_1} \tag{5.3}$$

and

$$g_1 > \frac{k \log\left(\frac{z_1 \mathfrak{n}_0}{2.71851} \prod_{p \le \mathfrak{m}} p^{\frac{2}{p^2-1}}\right) + (k+\frac{1}{2})\log(1-\frac{g_1}{k})}{\log(k-g_1) - 1 + \log z_1} - \frac{(1.5\pi(\mathfrak{m}) - 0.5\ell - 1)\log k + \log\left(\mathfrak{n}_1^{-1}\mathfrak{n}_2\prod_{p\le\mathfrak{m}} p^{0.5+\frac{2}{p^2-1}}\right)}{\log(k-g_1) - 1 + \log z_1} \tag{5.4}$$

where

$$\mathfrak{n}(k,p) = \begin{cases} [\frac{\log(k-1)}{\log p}] & \text{if } [\frac{\log(k-1)}{\log p}] \text{ is even} \\ [\frac{\log(k-1)}{\log p}] - 1 & \text{if } [\frac{\log(k-1)}{\log p}] \text{ is odd,} \end{cases}$$

$$\ell = |\{p \le \mathfrak{m} : p|d\}|,\ \mathfrak{n}_0 = \prod_{\substack{p|d \\ p\le\mathfrak{m}}} p^{\frac{1}{p+1}},\ \mathfrak{n}_1 = \prod_{\substack{p|d \\ p\le\mathfrak{m}}} p^{\frac{p-1}{2(p+1)}} \text{ and } \mathfrak{n}_2 = \begin{cases} 2^{\frac{1}{6}} & \text{if } 2 \nmid d \\ 1 & \text{otherwise.} \end{cases}$$

Proof. Since $|R| \ge t - g + 1 = k - g_1 + i_0$, we get

$$\prod_{b_i \in R} b_i \ge z_1^{k-g_1}(k-g_1)!. \tag{5.5}$$

Let

$$\vartheta_p = \mathrm{ord}_p\left(\prod_{b_i\in R} b_i\right),\ \vartheta'_p = 1 + \mathrm{ord}_p((k-1)!).$$

Let h be the positive integer such that $p^h \le k-1 < p^{h+1}$ and $\epsilon = 1$ or 0 according as h is even or odd, respectively. Then

$$\vartheta'_p - 1 = \left[\frac{k-1}{p}\right] + \left[\frac{k-1}{p^2}\right] + \cdots + \left[\frac{k-1}{p^h}\right]. \tag{5.6}$$

Let $p \nmid d$. We show that

$$\vartheta_p - \vartheta'_p < -\frac{2k}{p^2-1}(1 - \frac{1}{p^{\mathfrak{n}(k,p)}}) + 1.5\mathfrak{n}(k,p) \tag{5.7}$$

$$< -\frac{2k}{p^2-1} + \frac{1.5\log k}{\log p} + 0.5 + \frac{2}{p^2-1} + \mathfrak{n}_3 \tag{5.8}$$

where $\mathfrak{n}_3 = \frac{1}{6}$ if $p = 2$ and 0 otherwise. We see that ϑ_p is the number of elements in $\{n+\gamma_1 d, n+\gamma_2 d, \ldots, n+\gamma_t d\}$ divisible by p to an odd power. For a positive integer s with $s \le h$, let $0 \le i_{p^s} < p^s$ be such that $p^s | n + i_{p^s} d$. Then we observe that p^s divides exactly $1 + \left[\frac{k-1-i_{p^s}}{p^s}\right]$ elements in $\{n, n+d, \ldots, n+(k-1)d\}$. After removing a term to which p appears to a maximal power, the number of remaining elements in $\{n, n+d, \ldots, n+(k-1)d\}$ divisible by p to an odd power is at most

$$\left[\frac{k-1-i_p}{p}\right] - \left[\frac{k-1-i_{p^2}}{p^2}\right] + \left[\frac{k-1-i_{p^3}}{p^3}\right] - \cdots + (-1)^\epsilon \left[\frac{k-1-i_{p^h}}{p^h}\right].$$

Since $\left[\frac{k}{p^s}\right] - 1 \le \left[\frac{k-1-i_{p^s}}{p^s}\right] \le \left[\frac{k-1}{p^s}\right]$, we obtain

$$\vartheta_p - 1 \le \left[\frac{k-1}{p}\right] - \left[\frac{k}{p^2}\right] + \left[\frac{k-1}{p^3}\right] - \cdots + (-1)^\epsilon \left[\frac{k-1+\epsilon}{p^h}\right] + \frac{h-1+\epsilon}{2}.$$

This with (5.6) implies

$$\vartheta_p - \vartheta'_p \le -\sum_{j=1}^{\frac{h-1+\epsilon}{2}} \left(\left[\frac{k-1}{p^{2j}}\right] + \left[\frac{k}{p^{2j}}\right]\right) + \frac{h-1+\epsilon}{2}. \tag{5.9}$$

Since $[\frac{k}{p^{2j}}] \ge [\frac{k-1}{p^{2j}}] \ge \frac{k-1}{p^{2j}} - 1 + \frac{1}{p^{2j}} = \frac{k}{p^{2j}} - 1$, we obtain

$$\vartheta_p - \vartheta'_p \le -2k \sum_{j=1}^{\frac{h-1+\epsilon}{2}} \frac{1}{p^2} + 1.5(h-1+\epsilon)$$

giving (5.7) since $\mathfrak{n}(k,p) = h-1+\epsilon$. Further from (5.7), $k \le p^{h+1}$ and $h < \frac{\log k}{\log p}$, we get

$$\vartheta_p - \vartheta'_p < -\frac{2k}{p^2-1} + \frac{1.5\log k}{\log p} + \frac{2p^{2-\epsilon}}{p^2-1} + 1.5(\epsilon - 1)$$

giving (5.8). For $p|d$, we get $\vartheta_p - \vartheta'_p = -1 - \mathrm{ord}_p(k-1)!$ which together with Lemma 5.1 (v) gives

$$\begin{aligned}\vartheta_p - \vartheta'_p &< -\frac{k}{p-1} + \frac{\log k}{\log p} + \frac{1}{p-1} \\ &< -\frac{2k}{p^2-1} + \frac{1.5\log k}{\log p} + 0.5 + \frac{2}{p^2-1} - \frac{k}{p+1} - \frac{0.5\log k}{\log p} - \frac{p-1}{2(p+1)}.\end{aligned} \tag{5.10}$$

For $\mathfrak{m} > 1$, we have

$$\prod_{b_i \in R} b_i \,\Big|\, (k-1)! \left(\prod_{p \le k} p\right) \prod_{p \le \mathfrak{m}} p^{\vartheta_p - \vartheta'_p}.$$

Therefore from Lemma 5.1 (iii), (5.10), (5.7) and (5.8), we have

$$\prod_{b_i \in R} b_i < k! k^{-0.5\ell - 1} \left(\mathfrak{n}_1^{-1} \prod_{p \le \mathfrak{m}} p^{1.5\mathfrak{n}(k,p)}\right) \left(\frac{\mathfrak{n}_0}{2.71851} \prod_{p \le \mathfrak{m}} p^{\frac{2}{p^2-1}(1 - \frac{1}{p^{\mathfrak{n}(k,p)}})}\right)^{-k} \tag{5.11}$$

and

$$\prod_{b_i\in R} b_i < k!k^{1.5\pi(\mathfrak{m})-.5\ell-1}\left(\mathfrak{n}_1^{-1}\mathfrak{n}_2\prod_{p\le\mathfrak{m}} p^{0.5+\frac{2}{p^2-1}}\right)\left(\frac{\mathfrak{n}_0}{2.71851}\prod_{p\le\mathfrak{m}} p^{\frac{2}{p^2-1}}\right)^{-k}. \tag{5.12}$$

Comparing (5.11) and (5.12) with (5.5), we get

$$\frac{z_1^{g_1}k!}{(k-g_1)!} > k^{0.5\ell+1}\left(\mathfrak{n}_1^{-1}\prod_{p\le\mathfrak{m}} p^{1.5\mathfrak{n}(k,p)}\right)^{-1}\left(\frac{z_1\mathfrak{n}_0}{2.71851}\prod_{p\le\mathfrak{m}} p^{\frac{2}{p^2-1}(1-\frac{1}{p^{\mathfrak{n}(k,p)}})}\right)^{k} \tag{5.13}$$

and

$$\frac{z_1^{g_1}k!}{(k-g_1)!} > k^{-1.5\pi(\mathfrak{m})+.5\ell+1}\left(\mathfrak{n}_1^{-1}\mathfrak{n}_2\prod_{p\le\mathfrak{m}} p^{0.5+\frac{2}{p^2-1}}\right)^{-1}\left(\frac{z_1\mathfrak{n}_0}{2.71851}\prod_{p\le\mathfrak{m}} p^{\frac{2}{p^2-1}}\right)^{k}. \tag{5.14}$$

By Lemma 5.2, we have

$$\frac{z_1^{g_1}k!}{(k-g_1)!} < z_1^{g_1}e^{-g_1}(k-g_1)^{g_1}\left(\frac{k}{k-g_1}\right)^{k+\frac{1}{2}} = \left(\frac{z_1(k-g_1)}{e}\right)^{g_1}\left(1-\frac{g_1}{k}\right)^{-k-\frac{1}{2}}.$$

This together with (5.13) and (5.14) imply the assertions (5.3) and (5.4), respectively. □

The inequality (5.8) corrects the corresponding inequality in [Lai06, p. 466, line 3 from the bottom] used in [Lai06, Lemma 13] but the proof of [Lai06, Lemma 13] remains unaffected.

We end this section with the following lemma which follow immediately from [Lai06, Lemma 10].

Lemma 5.5. *Let $t=k$. Let $c>0$ be such that $c2^{\omega(d)-3}>248$, $\mu\ge 2$ and*

$$\mathfrak{C}_\mu = \{A_i : i\in T_1,\ \nu(A_i)=\mu,\ A_i > \frac{\rho 2^\delta k}{3c2^{\omega(d)}}\}.$$

Then

$$\mathfrak{C} := \sum_{\mu\ge 2}\frac{\mu(\mu-1)}{2}|\mathfrak{C}_\mu| \le \frac{3c}{32}4^{\omega(d)}(\log c2^{\omega(d)-3}). \tag{5.15}$$

6. Some counting functions

Let p be a prime $\le k$ and coprime to d. Then the number of i's for which b_i are divisible by q is at most

$$\sigma_q = \lceil\frac{k}{q}\rceil.$$

Let $r\ge 5$ be any positive integer. Define $F(k,r)$ and $F'(k,r)$ as

$$F(k,r) = |\{i : P(b_i) > p_r\}| \text{ and } F'(k,r) = \sum_{i=r+1}^{\pi(k)}\sigma_{p_i}.$$

Then $|\{b_i : P(b_i) > p_r\}| \le F(k,r) \le F'(k,r) - \sum_{p|d, p>p_r}\sigma_p$. Let

$$\mathcal{B}_r = \{b_i : P(b_i)\le p_r\},\ I_r = \{i : b_i\in\mathcal{B}_r\} \text{ and } \xi_r = |I_r|.$$

We have

$$\xi_r \ge t - F(k,r) \ge t - F'(k,r) + \sum_{p|d,p>p_r}\sigma_p \tag{6.1}$$

and

$$t-|R| \geq t-|\{b_i : P(b_i) > p_r\}| - |\{b_i : P(b_i) \leq p_r\}| \tag{6.2}$$

$$\geq t - F(k,r) - |\{b_i : P(b_i) \leq p_r\}| \tag{6.3}$$

$$\geq t - F'(k,r) + \sum_{p|d, p>p_r} \sigma_p - |\{b_i : P(b_i) \leq p_r\}| \tag{6.4}$$

$$\geq t - F'(k,r) + \sum_{p|d, p>p_r} \sigma_p - 2^r. \tag{6.5}$$

We write $\mathcal{S} := \mathcal{S}(r)$ for the set of positive squarefree integers composed of primes $\leq p_r$. Let $\delta = \min\{3, \text{ord}_2(d)\}$. Let $p = q = 2^\delta$ or $p \leq q$ be odd primes dividing d. Let $p = q = 2^\delta$. Then $b_i \equiv n (\text{mod } 2^\delta)$. Considering modulo 2^δ for elements of $\mathcal{S}(r)$, we see by induction on r that

$$|\{b_i : P(b_i) \leq p_r\}| \leq 2^{r-\delta} =: g_{2^\delta, 2^\delta} =: g_{2^\delta}. \tag{6.6}$$

For any odd prime p dividing d, all b_i's are either quadratic residues mod p or non-quadratic residues mod p. For odd primes p, q dividing d with $p \leq q$, we consider four sets:

$$\begin{aligned}
\mathcal{S}_1(n',r) &= \mathcal{S}_1(\delta, n', p, q, r) = \{s \in \mathcal{S} : s \equiv n' (\text{mod } 2^\delta), \left(\frac{s}{p}\right) = 1, \left(\frac{s}{q}\right) = 1\}, \\
\mathcal{S}_2(n',r) &= \mathcal{S}_2(\delta, n', p, q, r) = \{s \in \mathcal{S} : s \equiv n' (\text{mod } 2^\delta), \left(\frac{s}{p}\right) = 1, \left(\frac{s}{q}\right) = -1\}, \\
\mathcal{S}_3(n',r) &= \mathcal{S}_3(\delta, n', p, q, r) = \{s \in \mathcal{S} : s \equiv n' (\text{mod } 2^\delta), \left(\frac{s}{p}\right) = -1, \left(\frac{s}{q}\right) = 1\}, \\
\mathcal{S}_4(n',r) &= \mathcal{S}_4(\delta, n', p, q, r) = \{s \in \mathcal{S} : s \equiv n' (\text{mod } 2^\delta), \left(\frac{s}{p}\right) = -1, \left(\frac{s}{q}\right) = -1\}.
\end{aligned} \tag{6.7}$$

We take $n' = 1$ if $\delta = 0, 1$; $n' = 1, 3$ if $\delta = 2$ and $n' = 1, 3, 5, 7$ if $\delta = 3$. Let

$$g_{p,q} := g_{p,q}(r) = \max_{n'} (|\mathcal{S}_1(n',r)|, |\mathcal{S}_2(n',r)|, |\mathcal{S}_3(n',r)|, |\mathcal{S}_4(n',r)|) \tag{6.8}$$

and we write $g_p = g_{p,p}$. Then

$$|\{b_i : P(b_i) \leq p_r\}| \leq g_{p,q}. \tag{6.9}$$

In view of (6.6) and (6.9), the inequality (6.4) is improved as

$$t - |R| \geq t - F'(k,r) + \sum_{p|d, p>p_r} \sigma_p - \min_{p|d, q|d} \{g_{p,q}\}. \tag{6.10}$$

We observe that $\gcd(s, pq) = 1$ for $s \in \mathcal{S}_l$, $1 \leq l \leq 4$. Hence we see that $\mathcal{S}_l(n', r+1) = \mathcal{S}_l(n', r)$ if $p = p_{r+1}$ or $q = p_{r+1}$ implying

$$g_{p,q}(r+1) = g_{p,q}(r) \text{ if } p = p_{r+1} \text{ or } q = p_{r+1}. \tag{6.11}$$

Assume that $p_{r+1} \notin \{p, q\}$. Let $1 \leq l \leq 4$. We write $\mathcal{S}'_l(n', r+1) = \{s : s \in \mathcal{S}_l(n', r+1), p_{r+1}|s\}$. Then $s = p_{r+1}s'$ with $P(s') \leq p_r$ whenever $s \in \mathcal{S}'_l(n', r+1)$. Let $l = 1$. Then $s' \equiv n' p_{r+1}^{-1} \equiv n'' (\text{mod } 2^\delta)$ where $n'' = 1$ if $\delta = 0, 1$; $n'' = 1, 3$ if $\delta = 2$ and $n'' = 1, 3, 5, 7$ if $\delta = 3$. Further $\left(\frac{s'}{p}\right) = \left(\frac{p_{r+1}}{p}\right)$ and $\left(\frac{s'}{q}\right) = \left(\frac{p_{r+1}}{q}\right)$ for $s \in \mathcal{S}'_l(r+1)$. This implies $\mathcal{S}'_1(n', r+1) = p_{r+1}\mathcal{S}_m(n'', r)$ for some $m, 1 \leq m \leq 4$. Therefore $|\mathcal{S}'_1(n', r+1)| \leq g_{p,q}(r)$ by (6.8). Similarly $|\mathcal{S}'_l(n', r+1)| \leq g_{p,q}(r)$ for each $l, 1 \leq 1 \leq 4$. Hence we get from $\mathcal{S}_l(n', r+1) = \mathcal{S}_l(n', r) \cup \mathcal{S}'_l(n', r+1)$ that

$$g_{p,q}(r+1) \le 2g_{p,q}(r). \tag{6.12}$$

We now use the above assertions to calculate $g_{p,q}$.

i) Let $5 \le r \le 7, p \le 547$ when $\delta = 0, 1$; $5 \le r \le 7, p \le 547$ when $\delta = 2$ and $5 \le r \le 7, p \le 89$ when $\delta = 3$. Then

$$g_p(r) = \begin{cases} \max(1, 2^{r-\delta-2}) & \text{if } p \le p_r \\ \max(1, 2^{r-\delta-1}) & \text{if } p > p_r \end{cases} \tag{6.13}$$

except when $\delta = 0, r = 5, p = 479$ where $g_p = 2^r$;
$\delta = 1, r = 5, p \in \{131, 421, 479\}$, $r = 6, p = 131$ where $g_p = 2^{r-\delta}$;
$\delta = 2, r = 5, p \in \{41, 101, 131, 331, 379, 421, 461, 479, 499\}$ where $g_p = 2^{r-\delta}$;
$\delta = 2, r = 6, p \in \{101, 131\}$, $r = 7, p = 101$ where $g_p = 2^{r-\delta}$;
$\delta = 3, r = 5, p = 3$ where $g_p = 2^{r-\delta-1}$, $r = 5, p = 41$ where $g_p = 2^{r-\delta}$.

ii) Let $5 \le r \le 7, p \le 19, q \le 193$, $23 \le p < q \le 97$ when $\delta = 0$ and $r = 5, 6, p < q \le 37$ when $\delta \ge 1$. Then

$$g_{p,q}(r) = \begin{cases} \max(1, 2^{r-\delta-4}) & \text{if } p < q \le p_r \\ \max(1, 2^{r-\delta-3}) & \text{if } p \le p_r < q \\ \max(1, 2^{r-\delta-2}) & \text{if } p_r < p < q \end{cases} \tag{6.14}$$

except when

$$\delta = 0 \text{ and } \begin{cases} r = 5, & g_{p,q} = 2^{r-2} \text{ for } (p,q) \in \{(5,43), (5,167), (7,113), (7,127), \\ & (7,137), (11,61), (11,179), (11,181)\}; \\ r = 5, & g_{p,q} = 2^{r-1} \text{ for } (p,q) \in \{(19,139), (23,73), (37,83)\}; \\ r = 6, & g_{p,q} = 2^{r-2} \text{ for } (p,q) = (7,137); \\ r = 6, & g_{p,q} = 2^{r-1} \text{ for } (p,q) = (37,83); \end{cases}$$

$$\delta = 1 \text{ and } \begin{cases} r = 5, & g_{p,q} = 2^{r-4} \text{ for } (p,q) \in \{(5,7), (5,11)\}; \\ r = 5, & g_{p,q} = 2^{r-3} \text{ for } (p,q) = (5,37); \\ r = 5, & g_{p,q} = 2^{r-2} \text{ for } (p,q) \in \{(13,23), (29,31)\}; \\ r = 6, & g_{p,q} = 2^{r-4} \text{ for } (p,q) = (5,7); \end{cases}$$

$$\delta = 2 \text{ and } \begin{cases} r = 5, & g_{p,q} = 2^{r-4} \text{ for } (p,q) \in \{(3,19), (5,17), (5,37), (7,13), \\ & (7,23), (7,29), (7,31), (11,19), (11,29), (11,31)\}; \\ r = 5, & g_{p,q} = 2^{r-3} \text{ for } (p,q) \in \{(13,23), (17,37), (29,31)\}; \\ r = 6, & g_{p,q} = 2^{r-5} \text{ for } (p,q) \in \{(5,7), (7,13)\}; \\ r = 6, & g_{p,q} = 2^{r-4} \text{ for } (p,q) \in \{(7,29), (11,31), (13,23)\}. \end{cases}$$

Now we combine (6.13), (6.14), (6.12) and (6.11). We obtain (6.13) with $=$ replaced by $\le$ for $r \ge 7$ and $p \le 89$ and we shall refer it as (6.13, $\le$). Further we obtain (6.14) with $=$ replaced by $\le$ for $r \ge 7$ and either $p < q \le 97$ when $\delta = 0$ or $p = 3, q = 5$ when $\delta \ge 1$ and we shall refer it as (6.14, $\le$).

7. Computational Lemmas

From now on, we take $t = k$. Thus $b_j = a_{j-1}, B_j = A_{j-1}, y_j = x_{j-1}$ and $Y_j = X_{j-1}$ for $1 \le j \le k$. Let $\bar{f}(x) = \lceil x \rceil - [\frac{\lceil x \rceil}{4}]$ for $x > 0$ and $\mathcal{K}_a = \frac{k}{a2^{3-\delta}}$ for $a \in R$. We now state a result which generalises [HiLaShTi06, Lemma 1].

Lemma 7.1. *Let $a \in R$ and μ be a positive integer. Let p, q be distinct odd primes.*
(i) Let $f_0(k,a,\delta) = \bar{f}(\mathcal{K}_a)$,

$$f_1(k,a,p,\mu,\delta) = \frac{p-1}{2}\sum_{l=0}^{\mu-1}\bar{f}(\frac{\mathcal{K}_a}{p^{2l+1}}) + \bar{f}(\frac{\mathcal{K}_a}{p^{2\mu}})$$

and

$$f_2(k,a,p,q,\mu,\delta) = \frac{p-1}{2}\sum_{l=0}^{\mu-1}\left(\frac{q-1}{2}\bar{f}(\frac{\mathcal{K}_a}{p^{2l+1}q}) + \bar{f}(\frac{\mathcal{K}_a}{p^{2l+1}q^2})\right) + \bar{f}(\frac{\mathcal{K}_a}{p^{2\mu}}).$$

Then

$$\nu_o(a) \le \begin{cases} f_0(k,a,\delta) & \\ f_1(k,a,p,\mu,\delta) & \text{if } p \nmid d \\ f_2(k,a,p,q,\mu,\delta) & \text{if } p \nmid d, q \nmid d. \end{cases} \tag{7.1}$$

(ii) Let d be odd. Let

$$g_0(k,a,\mu) = \sum_{l=1}^{\mu-1}\bar{f}(\frac{\mathcal{K}_a}{2^{2l}}) + \bar{f}(\frac{k}{a2^{2\mu}}),$$

$$g_1(k,a,p,\mu) = \frac{p-1}{2}\sum_{l=0}^{\mu-1}\sum_{j=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j p^{2l+1}}) + \sum_{j=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j p^{2\mu}})$$

and

$$g_2(k,a,p,q,\mu) = \frac{p-1}{2}\sum_{l=0}^{\mu-1}\sum_{j=1}^{2}\left(\frac{q-1}{2}\bar{f}(\frac{\mathcal{K}_a}{2^j p^{2l+1}q}) + \bar{f}(\frac{\mathcal{K}_a}{2^j p^{2l+1}q^2})\right) + \sum_{j=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j p^{2\mu}}).$$

Then

$$\nu_e(a) \le \begin{cases} g_0(k,a,\mu) & \\ g_1(k,a,p,\mu) & \text{if } p \nmid d \\ g_2(k,a,p,q,\mu) & \text{if } p \nmid d, q \nmid d. \end{cases} \tag{7.2}$$

Proof. Let $\mathcal{I} \subseteq \{i : a_i = a\}$ and $\tau|(i-j)$ whenever $i, j \in \mathcal{I}$. Let τ' be the lcm of all τ_1 such that $\tau_1|(i-j)$ whenever $i, j \in \mathcal{I}$. Then $\tau|\tau'$ and $a|\tau'$ since $a|(i-j)$ whenever $i, j \in \mathcal{I}$. Let $i_0 = \min_{i\in\mathcal{I}} i$, $N = \frac{n+i_0 d}{a}$ and $D = \frac{\tau'}{a}d$. Then we see that ax_i^2 with $i \in \mathcal{I}$ come from the squares in the set $\{N, N+D, \cdots, N+(\lceil\frac{k-i_0}{\tau}\rceil - 1)D\}$. Dividing this set into consecutive intervals of length 4 and using Euler's result, we see that there are at most $\lceil\frac{k-i_0}{\tau'}\rceil - [\frac{\lceil\frac{k-i_0}{\tau'}\rceil}{4}] \le \lceil\frac{k}{\tau'}\rceil - [\frac{\lceil\frac{k}{\tau'}\rceil}{4}] = \bar{f}(\frac{k}{\tau'})$ of them which can be squares. Hence $|\mathcal{I}| \le \bar{f}(\frac{k}{\tau'}) \le \bar{f}(\frac{k}{\tau})$ since $\tau|\tau'$.

Let $\mathcal{I}^o = \{i : a_i = a, 2 \nmid x_i\}$ and $\mathcal{I}^e = \{i : a_i = a, 2|x_i\}$. Then $\nu_o(a) = |\mathcal{I}^o|$ and $\nu_e(a) = |\mathcal{I}^e|$.

First we prove (7.1). For $i, j \in \mathcal{I}^o$, we observe from $x_i^2, x_j^2 \equiv 1 (\mathrm{mod}\ 8)$ and $(i-j)d = a(x_i^2 - x_j^2)$ that $a2^{3-\delta}|(i-j)$. Therefore $|\mathcal{I}^o| \le \bar{f}(\mathcal{K}_a) = f_0(k,a,\delta)$.

For a prime p', let

$$\mathfrak{Q}_{p'} = \{m : 1 \le m < p', \left(\frac{m}{p'}\right) = 1\}.$$

Let $p \nmid d$. Let

$$\mathcal{I}_l^o = \{i \in \mathcal{I}^o : p^l||x_i\} \text{ for } 0 \le l < \mu \text{ and } \mathcal{I}_\mu^o = \{i \in \mathcal{I}^o : p^\mu|x_i\}.$$

Then $a2^{3-\delta}p^{2\mu}|(i-j)$ whenever $i,j \in \mathcal{I}^o_\mu$ giving $|\mathcal{I}^o_\mu| \le \bar{f}(\frac{\mathcal{K}_a}{p^{2\mu}})$. For each $l, 0 \le l < \mu$ and for each $m \in \mathfrak{Q}_p$, let

$$\mathcal{I}^o_{lm} = \{i \in \mathcal{I}^o_l : (\frac{x_i}{p^l})^2 \equiv m (\mathrm{mod}\ p)\}.$$

Then $a2^{3-\delta}p^{2l+1}|(i-j)$ whenever $i,j \in \mathcal{I}^o_{lm}$ giving $|\mathcal{I}^o_{lm}| \le \bar{f}(\frac{\mathcal{K}_a}{p^{2l+1}})$. Therefore $|\mathcal{I}^o_l| = \sum_{m\in\mathfrak{Q}_p} |\mathcal{I}^o_{lm}| \le \frac{p-1}{2}\bar{f}(\frac{\mathcal{K}_a}{p^{2l+1}})$. Hence $|\mathcal{I}^o| = |\mathcal{I}^o_\mu| + \sum_{l=0}^{\mu-1} |\mathcal{I}^o_l| \le f_1(k,a,p,\mu,\delta)$.

Thus we may assume that $p \nmid d$ and $q \nmid d$. For each l with $0 \le l < \mu$, $m \in \mathfrak{Q}_p$ and for each $u \in \mathfrak{Q}_q$, let

$$\mathcal{I}^o_{lmu} = \{i \in \mathcal{I}^o_{lm} : x_i^2 \equiv u (\mathrm{mod}\ q)\} \text{ and } \mathcal{I}^o_{lm0} = \{i \in \mathcal{I}^o_{lm} : q|x_i)\}.$$

Then $a2^{3-\delta}p^{2l+1}q|(i-j)$ for $i,j \in \mathcal{I}^o_{lmu}$ and $a2^{3-\delta}p^{2l+1}q^2|(i-j)$ for $i,j \in \mathcal{I}^o_{lm0}$ implying $|\mathcal{I}^o_{lmu}| \le \bar{f}(\frac{\mathcal{K}_a}{p^{2l+1}q})$ for $u \in \mathfrak{Q}_q$ and $|\mathcal{I}^o_{lm0}| \le \bar{f}(\frac{\mathcal{K}_a}{p^{2l+1}q^2})$. Now the assertion $\nu_o(a) \le f_2(k,a,p,q,\mu,\delta)$ follows from

$$|\mathcal{I}^o_{lm}| \le |\mathcal{I}^o_{lm0}| + \sum_{u\in\mathfrak{Q}_q} |\mathcal{I}^o_{lmu}|, |\mathcal{I}^o_l| = \sum_{m\in\mathfrak{Q}_p} |\mathcal{I}^o_{lm}|, \text{ and } |\mathcal{I}^o| = |\mathcal{I}^o_\mu| + \sum_{l=0}^{\mu-1} |\mathcal{I}^o_l|.$$

Now we turn to the proof of (7.2). Let

$$\mathcal{I}^{el} = \{i \in \mathcal{I}^e : 2^l||x_i\} \text{ for } 1 \le l < \mu \text{ and } \mathcal{I}^{e\mu} = \{i \in \mathcal{I}^e : 2^\mu|x_i\}.$$

Since $\frac{x_i}{2^l}$ is odd, we get $a2^{2l+3}|(i-j)$ whenever $i,j \in \mathcal{I}^{el}$ implying $|\mathcal{I}^{el}| \le \bar{f}(\frac{\mathcal{K}_a}{2^{2l}})$ for $0 \le l < \mu$. Further $a2^{2\mu}|(i-j)$ for $i,j \in \mathcal{I}^{e\mu}$ giving $|\mathcal{I}^{e\mu}| \le \bar{f}(\frac{k}{a2^{2\mu}})$. Now the assertion $\nu_e(a) \le g_0(k,a,\mu)$ from $|\mathcal{I}^e| = |\mathcal{I}^{e\mu}| + \sum_{l<\mu} |\mathcal{I}^{el}|$.

For the remaining proofs of (7.2), we consider $\mathcal{I}^{e1} = \{i \in \mathcal{I}^e : 2||x_i\}$, $\mathcal{I}^{e2} = \{i \in \mathcal{I}^e : 4|x_i\}$ so that $|\mathcal{I}^e| = |\mathcal{I}^{e1}| + |\mathcal{I}^{e2}|$. Then $32a|(i-j)$ for $i,j \in \mathcal{I}^{e1}$ and $16a|(i-j)$ for $i,j \in \mathcal{I}^{e2}$. We now continue the proof as in that of (7.1) with $\mathcal{I}^{e1}$, $\mathcal{I}^{e2}$ in place of $\mathcal{I}^o$ to get $\nu_e(a) \le g_1(k,a,p,\mu)$ when $p \nmid d$ and $\nu_e(a) \le g_2(k,a,p,q,\mu)$ when $p \nmid d, q \nmid d$. $\square$

Lemma 7.2. *For $a \in R$, let*

$$f_3(k,a,\delta) = \begin{cases} 1 & \text{if } k \le a2^{3-\delta} \\ \bar{f}(\mathcal{K}_a) & \text{if } k > a2^{3-\delta}, 3|d, 5|d \\ \bar{f}(\frac{\mathcal{K}_a}{3}) + \bar{f}(\frac{\mathcal{K}_a}{9}) & \text{if } k > a2^{3-\delta}, 3\nmid d, 5|d \\ \bar{f}(\mathcal{K}_a) & \text{if } a2^{3-\delta} < k \le 2a2^{3-\delta}, 3|d, 5\nmid d \\ 2\bar{f}(\frac{\mathcal{K}_a}{5}) + \bar{f}(\frac{\mathcal{K}_a}{25}) & \text{if } k > 2a2^{3-\delta}, 3|d, 5\nmid d \\ \bar{f}(\frac{\mathcal{K}_a}{3}) + \bar{f}(\frac{\mathcal{K}_a}{9}) & \text{if } a2^{3-\delta} < k \le 24a2^{3-\delta}, 3\nmid d, 5\nmid d \\ 2\left(\bar{f}(\frac{\mathcal{K}_a}{15}) + \bar{f}(\frac{\mathcal{K}_a}{135})\right) + & \\ \bar{f}(\frac{\mathcal{K}_a}{75}) + \bar{f}(\frac{\mathcal{K}_a}{675}) + \bar{f}(\frac{\mathcal{K}_a}{81}) & \text{if } 24a2^{3-\delta} < k \le 324a2^{3-\delta}, 3\nmid d, 5\nmid d \\ 2\left(\bar{f}(\frac{\mathcal{K}_a}{15}) + \bar{f}(\frac{\mathcal{K}_a}{135}) + \bar{f}(\frac{\mathcal{K}_a}{1215})\right) + & \\ \bar{f}(\frac{\mathcal{K}_a}{75}) + \bar{f}(\frac{\mathcal{K}_a}{675}) + \bar{f}(\frac{\mathcal{K}_a}{6075}) + \bar{f}(\frac{\mathcal{K}_a}{729}) & \text{if } k > 324a2^{3-\delta}, 3\nmid d, 5\nmid d \end{cases}$$

and

$$g_3(k,a)=\begin{cases}1 & \text{if } k\le 4a\\ \sum_{j=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j}) & \text{if } 4a<k\le 32a\\ \sum_{j=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j}) & k>32a, 3|d, 5|d\\ \sum_{j=1}^{2}\left(\bar{f}(\frac{\mathcal{K}_a}{2\cdot 3^j})+\bar{f}(\frac{\mathcal{K}_a}{4\cdot 3^j})\right) & \text{if } k>32a, 3\nmid d, 5|d\\ \sum_{j=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j}) & 32a<k\le 64a, 3|d, 5\nmid d\\ 2\sum_{j=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j.5})+\sum_{j=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j\cdot 25}) & \text{if } k>64a, 3|d, 5\nmid d\\ \sum_{j=1}^{2}\sum_{l=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j\cdot 3^l}) & \text{if } 32a<k\le 576a, 3\nmid d, 5\nmid d\\ 2\sum_{j=1}^{2}\sum_{l=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j.3^{2l-1}.5})+ & \\ \sum_{j=1}^{2}\sum_{l=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j\cdot 3^{2l-1}\cdot 25})+\sum_{j=1}^{2}\bar{f}(\frac{\mathcal{K}_a}{2^j\cdot 81}) & \text{if } k>576a, 3\nmid d, 5\nmid d.\end{cases}$$

Then for $a\in R$, we have

$$\nu_o(a)\le f_3(k,a,\delta),\ \nu_e(a)\le g_3(k,a)$$

and

$$\nu(a)\le F_0(k,a,\delta):=\begin{cases}1 & \text{if } k\le a\\ f_3(k,a,\delta) & \text{if } k>a \text{ and } d \text{ even}\\ f_3(k,a,0)+g_3(k,a) & \text{if } k>a \text{ and } d \text{ odd.}\end{cases}$$

Proof. Since $a|(i-j)$ whenever $a_i=a_j=a$, we get $\nu(a)\le 1$, $\nu_o(a)\le 1$, $\nu_e(a)\le 1$ for $k\le a$. In fact $\nu_o(a)\le 1$ for $k\le a2^{3-\delta}$ and $\nu_e(a)\le 1$ for $k\le 4a$. Thus we suppose that $k>a$. We have $\nu(a)=\nu_o(a)+\nu_e(a)$. It suffices to show $\nu_o(a)\le f_3(k,a,\delta)$ for $k>a2^{3-\delta}$ and $\nu_e(a)\le g_3(k,a)$ for $k>4a$ since $\nu_e(a)=0$ for d even. From (7.1), we get the assertion $\nu_o(a)\le f_3(k,a,\delta)$ for $k>a2^{3-\delta}$ since

$$\nu_o(a)\le\begin{cases}f_0(k,a,\delta) & \text{if } 15|d\\ f_1(k,a,3,1,\delta) & \text{if } 3\nmid d, 5|d\\ \min(f_0(k,a,\delta), f_1(k,a,5,1,\delta)) & \text{if } 3|d, 5\nmid d\\ \min(f_1(k,a,3,1,\delta), f_2(k,a,3,5,2,\delta), & \\ \ f_2(k,a,3,5,3,\delta)) & \text{if } 3\nmid d, 5\nmid d.\end{cases}$$

The assertion $\nu_e(a)\le g_3(k,a)$ for $k>4a$ follows from (7.2) since $\nu_e(a)\le g_0(k,a,2)$ for $4a<k\le 32a$ and

$$\nu_e(a)\le\begin{cases}g_0(k,a,2) & \text{if } 15|d\\ g_1(k,a,3,1)) & \text{if } 3\nmid d, 5|d\\ \min(g_0(k,a,2), g_1(k,a,5,1)) & \text{if } 3|d, 5\nmid d\\ \min(g_1(k,a,3,1), g_2(k,a,3,5,2)) & \text{if } 3\nmid d, 5\nmid d\end{cases}$$

for $k>32a$. □

By applying that there are $\frac{p-1}{2}$ distinct quadratic residues and $\frac{p-1}{2}$ distinct quadratic nonresidues modulo a prime p, we have

Lemma 7.3. *Assume* (1.1) *holds with $k\nmid d$. Then $\nu(a)\le\frac{k-1}{2}$ for any $a\in R$.*

Lemma 7.4. *Suppose that* (1.1) *with $P(b)\le k$ and $k=p_m$ has no solution. Then* (1.1) *with $P(b)\le k$ and $p_m\le k<p_{m+1}$ has no solution.*

Proof. Let $p_m\le k<p_{m+1}$. Suppose (n,d,b,y) is a solution of

$$n(n+d)\cdots(n+(k-1)d)=by^2$$

with $P(b)\le k$. Then $P(b)\le p_m$ and by (1.5),

$$n(n+d)\cdots(n+(p_m-1)d)=b'y'^2$$

holds for some b' with $P(b')\le p_m$ giving a solution of (1.1) at $k=p_m$. This is a contradiction. □

Lemma 7.5. *Let* $k\ge 101$. *Assume* (1.1).
(a) *Let d be odd and $p<q$ be primes such that $pq|d$ with $p\le 19, q\le 47$. Then $k\ge 1733$.*
(b) *Let d be odd and $p<q$ be primes such that $pq|d$ with $23\le p<q\le 43, (p,q)\ne(31,41)$. Then $k\ge 1087$.*
(c) *Let d be even such that $p|d$ with $3\le p\le 47$. Then $k\ge 1801$.*

Proof. We shall use the notation and results of Section 6 without reference. By Lemma 7.4, it suffices to prove Lemma 7.5 when k is a prime. Let P_0 be the largest prime $\le k$ such that $P_0\nmid d$. Then (1.1) holds at $k=P_0$. Therefore $P_0\ge 101$ by Theorem $\mathcal{A}$ with $k=97$. Thus there is no loss of generality in assuming that $k\nmid d$ for the proof of Lemma 7.5.
(a) Let d be odd and p,q be as in (a). Assume $k<1733$. It suffices to consider 4 cases, viz (i) $5<p<q, 3\nmid d, 5\nmid d$; ($ii$) $p=3, q>5, 5\nmid d$; (iii) $p=5, q>5, 3\nmid d$ and (iv) $p=3, q=5$. We take $r\ge 7$. We see that $\mathcal{B}_r$ is contained in one of the four sets $\mathcal{S}_\mu=\mathcal{S}_\mu(1,r)$ with $1\le\mu\le 4$. Let $\mathcal{S}'_\mu=\{s\in\mathcal{S}_\mu : s<2000\}$ with $1\le\mu\le 4$. We have $\nu(s)\le F_0(k,s,0)$ by Lemma 7.2. Further $\nu(s)\le 1$ for $s\ge k$ and hence for $s\in\mathcal{S}_\mu\setminus\mathcal{S}'_\mu$. Observe that $1\in\mathcal{S}'_1\subseteq\mathcal{S}_1$.

Assume that $1\notin R$ in the case (iv). For the case (i), we take $r=7$ for $101\le k<1087$ and $r=8$ for $1087\le k<1733$. For all other cases, we take $r=7$ for $101\le k<941$, $r=8$ for $941\le k<1297$ and $r=9$ for $1297\le k<1733$. Then $\xi_r\le\max\sum_{s\in\mathcal{S}_\mu}\nu(s)\le\max\left(g_{p,q}-|\mathcal{S}'_\mu|+\sum_{s\in\mathcal{S}'_\mu}F(k,s,0)\right)\le g_{p,q}+\max\sum_{s\in\mathcal{S}'_\mu}(F_0(k,s,0)-1)=:\tilde{\xi_r}$ where the maximum is taken over $1\le\mu\le 4$ and we remove 1 from $\mathcal{S}'_1\subseteq\mathcal{S}_1$ when the case (iv) holds. We now check that

$$k-F'(k,r)-\tilde{\xi_r}>\begin{cases}0 & \text{if } p<q\le p_r\\ -\lceil\frac{k}{q}\rceil & \text{if } p\le\mathfrak{p}_r<q\\ -\lceil\frac{k}{p}\rceil-\lceil\frac{k}{q}\rceil & \text{if } \mathfrak{p}_r<p<q.\end{cases}\tag{7.3}$$

This contradicts (6.1) by using the estimates for $g_{p,q}$ and $\tilde{\xi_r}\ge\xi_r$.

Thus it remains to consider (iv) with $1\in R$. Then $\left(\frac{a_i}{3}\right)=\left(\frac{a_i}{5}\right)=1$ for all $a_i\in R$. Suppose that $p'\nmid d$ for some prime $p'\in\mathcal{P}=\{7,11,13\}$. We take $r=9$. We have $\mathcal{B}_r\subseteq\mathcal{S}_1$. Further $|\mathcal{S}_1|=32$ and $\mathcal{S}'_1=\{1,19,34,46,91,154,286,$
$391,646,874,1309,1729,1771\}$. We get from (7.1) that $\nu_o(a)\le\min(f_0(k,a,0),$
$f_1(k,a,p',1,0))\le\min(f_0(k,a,0),\max_{p'\in\mathcal{P}}\{f_1(k,a,p',1,0)\}):=G_1(k,a)$. Similarly we get from (7.2) that $\nu_e(a)\le\min(g_0(k,a,2),\max_{p'\in\mathcal{P}}\{g_1(k,a,p',1,0)\}:=G_2(k,a)$. Let $G(k,a)=1$ if $k\le a$ and $G(k,a)=G_1(k,a)+G_2(k,a)$ if $k>a$. Then $\nu(a)\le G(k,a)$ implying $\xi_r\le 32+\sum_{s\in\mathcal{S}'_1}(G(k,s)-1)=:\tilde{\xi_r}$ as above. We check that

$$k-F'(k,r)-\tilde{\xi_r}>0.\tag{7.4}$$

This contradicts (6.1). Thus $p'|d$ for each prime $p\in\mathcal{P}$. Now we take $r=14$. Since $1\in R$, we have $\left(\frac{a_i}{p}\right)=1$ for all $a_i\in R$ and for each p with $3\le p\le 13$. Therefore $\mathcal{B}_r\subseteq\{s\in\mathcal{S}(r):\left(\frac{s}{p}\right)=1, 3\le p\le 13\}=\{1,1054\}\cup\mathcal{S}''$ where $|\mathcal{S}''|=14$ and $s>2000$ for each $s\in\mathcal{S}''$. Hence $\xi_r\le\nu(1)+\nu(1054)+14\le\nu(1)+16$

since $\nu(1054) \le 2$ by Lemma 7.2. From (7.1) and (7.2) with $\mu = 3$, we get $\nu(1) \le f_0(k,1,0) + g_0(k,1,3)$. Therefore $\xi_r \le f_0(k,1,0) + g_0(k,1,3) + 16 =: \tilde{\xi_r}$ and we compute that (7.4) holds contradicting (6.1).

(*b*) Let d be odd and p, q be as in (*b*). Assume $k < 1013$. By (*a*), we may assume that $3 \nmid d, 5 \nmid d$. We continue the proof as above in the case (*i*) of (*a*). We take $r = 7$ and check that $k - F'(k,r) - \tilde{\xi_r} + \lceil \frac{k}{p} \rceil + \lceil \frac{k}{q} \rceil > 0$. This contradicts (6.1).

(*c*) Let d be even and p be as in (*c*). Assume $k < 1801$. For any set W of squarefree integers, let $W' = W'(\delta) = \{s \in W : s < \frac{2000}{2^{3-\delta}}\}$. We consider four cases, viz (*i*) $p > 5, 3 \nmid d, 5 \nmid d$; (*ii*) $p = 5, 3 \nmid d$; (*iii*) $p = 3, 5 \nmid d$ and (*iv*) $15|d$. We take $r \ge 7$. Assume that $(i), (ii)$ or (iii) holds. Then from (6.7) with $p = q$, we get 2^δ sets $U_\mu, 1 \le \mu \le 2^\delta$ given by $\mathcal{S}_1(n', r), \mathcal{S}_4(n', r)$. Without loss of generality, we put $\mathcal{S}_1(1, r) = U_1$. Further $|U_\mu| \le g_p$ for $1 \le \mu \le 2^\delta$. Assume (*iv*). We take $p = 3, q = 5$ in (6.7). We get $2^{\delta+1}$ sets $V_\mu, 1 \le \mu \le 2^{\delta+1}$ given by $\mathcal{S}_j(n', r), 1 \le j \le 4$ and we put $\mathcal{S}_1(1, r) = V_1$. Further $|V_\mu| \le 2^{r-\delta-4}$ for $1 \le \mu \le 2^{\delta+1}$. We define g' by $g' = 2^{r-\delta-4}$ if (*iv*) holds and $g' = g_p$ otherwise. Further let W_μ with $1 \le \mu \le 2^{\delta+1}$ be given by $W_\mu = V_\mu$ if (*iv*) holds and $W_\mu = U_\mu$ for $1 \le \mu \le 2^\delta$, $W_\mu = \emptyset$ for $\mu > 2^\delta$ if $(i), (ii)$ or (iii) holds. We see from Lemma 7.2 that $\nu(s) \le F_0(k, s, \delta)$ and $\nu(s) \le 1$ for $s \in W_\mu \setminus W'_\mu$. Observe that $1 \in W'_1 \subseteq W_1$.

Assume that $1 \notin R$ in the cases $(ii), (iii)$ or (iv). We take $r = 8$ for $101 \le k \le 941$, $r = 9$ for $941 < k \le 1373$ and $r = 10$ for $1373 < k < 1801$ in the case (*i*) with $8|d$. For all other cases, we take $r = 7$ for $101 \le k \le 941$, $r = 8$ for $941 < k \le 1373$ and $r = 9$ for $1373 < k < 1801$. Then $\xi_r \le \max \sum_{s \in W_\mu} F(k, s, \delta) \le g' + \max \sum_{s \in W'_\mu} (F_0(k, s, \delta) - 1) =: \tilde{\xi_r}$ where maximum is taken over $1 \le \mu \le 2^{\delta+1}$ and we remove 1 from $W'_1 \subseteq W_1$ when $(ii), (iii)$ or (iv) holds. We check that

$$k - F'(k,r) - \tilde{\xi_r} > \begin{cases} -\lceil \frac{k}{p} \rceil & \text{if } (i) \text{ holds with } p > p_r \\ 0 & \text{otherwise.} \end{cases}$$

This contradicts (6.1).

Thus it remains to consider the cases $(ii), (iii)$ or (iv) and $1 \in R$. Then $a_i \equiv 1 (\text{mod } 2^\delta)$ and $\left(\frac{a_i}{p}\right) = 1$ for all $p|d$ whenever $a_i \in R$. Let $P_0 = \{5\}, \{3\}, \{3, 5\}$ when $(ii), (iii), (iv)$ holds, respectively. Then $\left(\frac{a_i}{p}\right) = 1$ for $p \in P_0$.

Assume that $7 \nmid d$ when $8|d, 15|d$. Let $\mathcal{P} = \{7\}$ if $8|d, 3|d, 5 \nmid d$; $\mathcal{P} = \{7, 11, 13, 17, 19\}$ if $4||d, 15|d$; $\mathcal{P} = \{11, 13, 17, 19\}$ if $8|d, 15|d$ and $\mathcal{P} = \{7, 11, 13\}$ in all other cases. Suppose that $p' \nmid d$ for some prime $p' \in \mathcal{P}$. Let r be given by the following table:

$(ii), (iii), 2\|\|d, 4\|\|d$	$(ii), (iii), 8\|d$	$(iv), 2\|\|d$	$(iv), 4\|\|d, 8\|d$
$\begin{cases} 8 & \text{for } k \le 941 \\ 9 & \text{for } k > 941 \end{cases}$	$\begin{cases} 10 & \text{for } k \le 941 \\ 11 & \text{for } k > 941 \end{cases}$	9	11

We get $\mathcal{B}_r \subseteq W_1$. For $s \in W'_1$, we get from (7.1) that $\nu(s) = \nu_o(s) \le G(k, s, \delta) :=\min(f_0(k, s, \delta), G_1, G_2)$ where

$$(G_1, G_2) = \begin{cases} (f_1(k,s,3,2,\delta), \max_{p' \in \mathcal{P}} f_2(k,s,3,p',2,\delta)) & \text{when } (ii) \text{ holds, } 8 \nmid d \\ (f_1(k,s,5,1,\delta), \max_{p' \in \mathcal{P}} f_2(k,s,5,p',1,\delta)) & \text{when } (iii) \text{ holds, } 8 \nmid d \\ (f_1(k,s,3,1,3), \max_{p' \in \mathcal{P}} f_2(k,s,3,p',2,3)) & \text{when } (ii) \text{ holds, } 8|d \\ (f_1(k,s,5,1,3), \max_{p' \in \mathcal{P}} f_2(k,s,5,p',2,3)) & \text{when } (iii) \text{ holds, } 8|d \end{cases}$$

and when (iv) holds, $G_1=G_2=\max_{p'\in\mathcal{P}} f_1(k,s,p',1,\delta)$ if $2||d$ or $4||d$, $G_1=G_2=\max_{p'\in\mathcal{P}} f_2(k,s,7,p',1,3)$ if $8|d$. Therefore $\xi_r\le g'+\sum_{s\in W_1'}(G(k,s,\delta)-1)=:\tilde{\xi_r}$. Now we check (7.4) contradicting (6.1). Thus $p'|d$ for each prime $p'\in\mathcal{P}$. Let r and g_1 be given by the following table:

Cases:	$(ii),(iii),2\|\|d$	$(ii),(iii),4\|\|d$	$(ii),8\|d$	$(iv),2\|\|d$	$(iv),8\|d$
(r,g_1)	$(12,8)$	$(12,4)$	$(15,16)$	$(13,4)$	$(17,4)$

Suppose that one of the above case hold. Then $\mathcal{B}_r\subseteq\{s\in\mathcal{S}(r): s\equiv 1(\text{mod } 2^\delta), \left(\frac{s}{p'}\right)=1, p'\in\mathcal{P}\cup\mathcal{P}_0\}=\{1\}\cup W''$ with $|W''|=g_1-1$ and $s\ge\frac{2000}{2^{3-\delta}}$ for $s\in W''$. Therefore $\xi_r\le\nu(1)+g_1-1$. From (7.1), we get $\nu(1)\le G(k)$ where $G(k)=f_1(k,1,3,2,\delta)$ if (ii) holds; $f_1(k,1,5,2,\delta)$ if (iii) holds, $8\nmid d$; $G(k)=f_0(k,1,1)$ if (iv) holds with $2||d$ and $G(k)=f_1(k,1,7,2,3)$ if (iv) holds with $8|d$. Therefore $\xi_r\le G(k)+g_1-1=:\tilde{\xi_r}$ and we compute that (7.4) holds. This contradicts (6.1). Thus either $(A):(iv)$ holds, $4||d$ or $(B):(iii)$ holds, $8|d$. Assume that $p'\nmid d$ with $p'\in\mathcal{P}_1$ where $\mathcal{P}_1=\{23,29,31,37\},\{11,13,17,19\}$ when $(A),(B)$ holds, respectively. In the remaining part of this paragraph, by 'respectively", we mean "when $(A),(B)$ holds, respectively'. We take $r=18,11$, respectively. Then $\mathcal{B}_r\subseteq\{s\in\mathcal{S}(r): s\equiv 1(\text{mod } 2^\delta), \left(\frac{s}{p'}\right)=1, p'\in\mathcal{P}\cup\mathcal{P}_0\}\subseteq\{1,1705\}\cup W''$ with $|W''|=g_1$ and $s\ge\frac{2000}{2^{3-\delta}}$ for $s\in W''$ where $g_1=3,14$, respectively. Hence $\xi_r\le\nu(1)+\nu(1705)+g_1\le G(k)+2+g_1=:\tilde{\xi_r}$ where $\nu(1)\le G(k)=\max_{p'\in\mathcal{P}_1} f_1(k,1,p',1,2),\max_{p'\in\mathcal{P}_1} f_2(k,1,5,p',1,3)$, respectively by (7.1). We check (7.4), contradicting (6.1). Thus $p'|d$ with $p'\le 37$ if (A) holds and $p'|d$ with $p'\le 19, p'\ne 5$ if (B) holds. Now we take $r=22,16$, respectively to get $\mathcal{B}_r\subseteq\{1\}\cup W''$ with $|W''|=g_2$ and $s\ge\frac{2000}{2^{3-\delta}}$ for $s\in W''$ where $g_2=0,3$, respectively. From (7.1), we get $\nu(1)\le G(k)$ with $G(k)=f_0(k,1,2),f_1(k,1,5,2,3)$, respectively. Hence $\xi_r\le G(k)+g_2=:\tilde{\xi_r}$ and we compute that (7.4) holds. This contradicts (6.1).

Thus it remains to consider the case (iv) with $8|d$ and $7|d$. Then

$$a_i\equiv 1(\text{mod } 8) \text{ and } \left(\frac{a_i}{p}\right)=1 \text{ for } p=3,5,7 \tag{7.5}$$

whenever $a_i\in R$. Let $k<263$. By taking $r=12$, we find that $\mathcal{B}_r\subseteq\{s\in\mathcal{S}(r): s\equiv 1(\text{mod } 8), \left(\frac{s}{p_j}\right)=1, 2\le j\le 4\}=\{1,6409,9361,12121,214489,$
$268801,4756609,59994649\}$. Then by Lemma 7.3, $\nu(1)\le\frac{k-1}{2}$ since $k\nmid d$ by our assumption. Further $\nu(6409)+\nu(268801)+\nu(4756609)+\nu(59994649)\le\lceil\frac{k}{13\cdot 29}\rceil\le 1$, $\nu(9361)+\nu(214489)\le\lceil\frac{k}{11\cdot 37}\rceil\le 1$ and $\nu(12121)\le 1$. Therefore $\xi_r\le\frac{k-1}{2}+3=:\tilde{\xi_r}$. We check (7.4) contradicting (6.1). Thus $k\ge 263$. By (7.5), we see that a_i is not a prime ≤ 89. Hence for $a_i\in R$ with $P(a_i)\le 89$, we have $\omega(a_i)\ge 2$. Further by (7.5), $a_i=p'q'$ with $11\le p'\le 37$ and $41\le q'\le 89$ is not possible. For integers P_1,P_2 with $P_1<P_2$, let

$$\mathcal{I}(P_1,P_2)=\{i: p'q'|a_i, P_1\le p'<q'\le P_2\}.$$

Then $|\mathcal{I}(P_1,P_2)|\le\sum_{P_1\le p'<q'\le P_2}\lceil\frac{k}{p'q'}\rceil$. Suppose that $p_j\nmid d$ for some prime $j\in\{5,6\}$. Then $\nu(1)\le G_0(k):=\max_{j=5,6} f_1(k,1,p_j,2,3)$ by (7.1). We take $r=23$. For $P_0\in\{11,13\}$, let $A(P_0)=\{a_i: a_i=P_0p'$ with $P_0<p'\le 37$ or $a_i=P_0p'q'$ with $P_0<p'\le 37, 41\le q'\le 83\}$. Then from (7.5), we get $A(11)\subseteq\{6721,8569,25201\}$ and $A(13)\subseteq\{17329,17641,27001\}$. Therefore we get from

$$\begin{aligned} I_r\subseteq&\{i: a_i=1\}\cup\mathcal{I}(17,37)\cup\mathcal{I}(41,83)\cup\\ &\{i: a_i\in A(11)\cup A(13)\}\cup\{i: 11\cdot 13p'|a_i, 17\le p'\le 37\}\end{aligned}$$

that

$$\xi_r \le G_0(k) + \sum_{17\le p'<q'\le 37} \lceil \frac{k}{p'q'} \rceil + \lceil \frac{k}{41\cdot 43} \rceil + 54 + 3 + 3 + 6 =: \tilde{\xi_r}$$

since $p'q' > k$ for $41 \le p' < q' \le 83$ except when $p' = 41, q' = 43$. Now we compute that (7.4) holds contradicting (6.1). Thus $p_j|d$ for $j \le 6$. Assume that $p_j \nmid d$ for some j with $7 \le j \le 9$. Then $\nu(1) \le G_1(k) := \max_{7\le j\le 9} f_1(k, 1, p_j, 1, 3)$ by (7.1). We take $r = 24$. Then $I_r \subseteq \{i : a_i = 1\} \cup \mathcal{I}(17, 37) \cup \mathcal{I}(41, 89)$. Therefore $\xi_r \le G_1(k) + \sum_{17\le p'<q'\le 37} \lceil \frac{k}{p'q'} \rceil + \lceil \frac{k}{41\cdot 43} \rceil + 65 =: \tilde{\xi_r}$ and we check (7.4). This contradicts (6.1). Thus $p_j|d$ for $j \le 9$. Suppose that $p_j \nmid d$ for some j with $10 \le j \le 14$. Then $\nu(1) \le G_2(k) := \max_{10\le j\le 14} f_1(k, 1, p_j, 1, 3)$ by (7.1). We take $r = 21$. Then $\mathcal{B}_r \subseteq \{s \in \mathcal{S}(r) : s \equiv 1(\text{mod } 8) \text{ and } \left(\frac{s}{p_i}\right) = 1, i \le 9\} = \{1, 241754041\}$ giving $\xi_r \le G_2(k) + 1 =: \tilde{\xi_r}$. Now we check (7.4) contradicting (6.1). Hence $p_j|d$ for $j \le 14$. Suppose that $p_j \nmid d$ for some j with $15 \le j \le 22$. Then $\nu(1) \le G_3(k) := \max_{15\le j\le 22} f_1(k, 1, p_j, 1, 3)$ by (7.1). We take $r = 26$. Then $\mathcal{B}_r \subseteq \{1\}$ as above giving $\xi_r \le G_2(k) =: \tilde{\xi_r}$. We compute that (7.4) holds contradicting (6.1). Thus $p_j|d$ for $j \le 22$. Finally we take $r = 32$. Then $\mathcal{B}_r \subseteq \{1\}$ as above giving $\xi_r \le \nu(1) \le \frac{k-1}{2} =: \tilde{\xi_r}$ by Lemma 7.3. We check (7.4). This contradicts (6.1). $\square$

Lemma 7.6. *We have*

$$k - |R| \ge g \text{ for } k \ge k_0(g) \tag{7.6}$$

where g and $k_0(g)$ are given by

(i)

g	9	14	17	29	33	61	65	129	256	2^s *with* $s \ge 9$, $s \in \mathbb{Z}$
$k_0(g)$	101	299	308	489	556	996	1057	2100	4252	$s2^{s+1}$

(ii) d even:

g	18	29	33	61	64	128	256	512	1024
$k_0(g)$	101	223	232	409	430	900	1895	4010	8500

(iii) $4||d$:

g	26	32	33	61	64	128	256	512	1024
$k_0(g)$	101	126	129	286	303	640	1345	2860	6100

(iv) $8|d$:

g	33	61	64	128	256	512	1024
$k_0(g)$	101	209	220	466	990	2110	4480

(v) $3|d$:

g	26	32	33	64	125	128	256	512
$k_0(g)$	101	126	129	351	720	735	1550	3300

(vi) $p|d$ with $p \in \{5, 7\}$:

g	33	64	128	256
$k_0(g)$	240	460	930	1940

Further we have $k_0(128) = 1200$ if $p|d$ with $p \le 19$ and $k_0(256) = 2870$ if $p|d$ with $p \le 47$.
(vii) Further $k_0(256) = 1115$ if $pq|d$ with $p \in \{5, 7, 11\}$; $k_0(256) = 1040$ if $2p|d$ with $p \in \{3, 5\}$; $k_0(512) = 1400$ if $105|d$; $k_0(512) = 1440$ if $30|d$ and $k_0(512) = 1480$ if $8p|d$ with $p \in \{3, 5\}$.

Proof. (i) Let g be given as in (i). Assume that $k \ge k_0(g)$ and $k - |R| < g$. We shall arrive at a contradiction.

Let $g\neq 9$. From (5.1), we have $\prod_{a_i\in R}a_i\ge (1.6)^{|R|}(|R|)!$ whenever $|R|\ge 286$. We observe that (5.3) and (5.4) hold with $i_0=0, h_0=286$, $z_1=1.6, g_1=g-1$, $\mathfrak{m}=$min(89, $\sqrt{k_0(g)}$)$, \ell=0, \mathfrak{n}_0=1, \mathfrak{n}_1=1$ and $\mathfrak{n}_2=2^{\frac{1}{6}}$ for $k\ge g_1+286$ and thus for $k\ge k_0(g)$.

Let $g=2^s$ with $s\ge 9$. Then $\frac{g_1}{k}\le\frac{2^s}{s2^{s+1}}\le\frac{1}{18}$ and we get from (5.4)

$$2^s-1>\frac{c_1k-c_2\log k-c_3}{\log c_4k}=\frac{c_1k-c_3+c_2\log c_4}{\log c_4k}-c_2 \tag{7.7}$$

where

$$c_1=\log\left(\frac{1.6}{2.71851}\prod_{p\le\mathfrak{m}}p^{\frac{2}{p^2-1}}\right)+\log(1-\frac{1}{18}),\ c_2=1.5\pi(\mathfrak{m})-1,$$

$$c_3=\log\left(2^{\frac{1}{6}}\prod_{p\le\mathfrak{m}}p^{0.5+\frac{2}{p^2-1}}\right)-\frac{1}{2}\log(1-\frac{1}{18}),\quad c_4=\frac{1.6}{e}$$

Here we check that $c_1k-c_2\log k-c_3>0$ at $k=9\cdot 2^{10}$ and hence (7.7) is valid. Further we observe that the right hand side of (7.7) is an increasing function of k. Putting $k=k_0(g)=s2^{s+1}$, we get from (7.7) that

$$2^s\left\{\frac{2c_1-\frac{c_3-c_2\log c_4}{s2^s}}{\log 2+\frac{\log(2c_4s)}{s}}-\frac{c_2-1}{2^s}-1\right\}<0.$$

The expression inside the brackets is an increasing function of s and it is positive at $s=9$. Hence (7.7) does not hold for all $k\ge k_0(g)$. Therefore $k-|R|\ge g=2^s$ whenever $s\ge 9$ and $k\ge s2^{s+1}$.

Let $g\in\{14,17,29,33,61,65,129,256\}$ and $k_1(g)=299,316,500,569,1014,$ $1076,2126,4295$ according as $g=14,17,29,33,61,65,129,256$, respectively. We see that the right hand side of (5.4) is an increasing function of k and we check that it exceeds g_1 at $k=k_1(g)$. Therefore (5.4) is not possible for $k\ge k_1(g)$. Thus $g\neq 14$ and $k<k_1(g)$. For every k with $k_0(g)\le k<k_1(g)$, we compute the right hand side of (5.3) and we find it greater than g_1. This is not possible.

Thus we may assume that $g=9$ and $k<299$. By taking $r=4$ for $101\le k\le 181$ and $r=5$ for $181<k<299$ in (6.3) and (6.5), we get $k-|R|\ge k-F'(k,r)-2^r\ge 9$ for $k\ge 101$ except when $103\le k\le 120, k\neq 106$ where $k-|R|\ge k-F(k,r)-2^r\ge k-F'(k,r)-2^r=8$. Let $103\le k\le 120, k\neq 106$. We may assume that $k-|R|=8$ and hence $F(k,r)=F'(k,r)$. Thus for each prime $11\le p\le k$, there are exactly σ_p number of i's for which $p|a_i$ and for any i, $pq\nmid a_i$ whenever $11\le q\le k, q\neq p$. Now we get a contradiction by considering the i's for which a_i's are divisible by primes $17,101; 103,17; 13,103; 53,13; 107,53; 11,109; 37,11; 19,113; 23,19; 29,23; 13,29; 59,13; 17,$ 59 when $k=103,104,105,107,108,111,112,115,116,117,118,119,120$, respectively; $107,53,13,103,17$ when $k=109$, $109,107,53$ when $k=110$; $37,11,109,107$ when $k=113$ and $113,37,11$ when $k=114$. For instance let $k=113$. Then $37|a_i$ for $i\in\{0,37,74,111\}$ or $i\in\{1,38,75,112\}$. We consider the first case and the other case follows similarly. Then $11|a_i$ for $i\in\{2+11j:0\le j\le 10\}$ and $109|a_i$ for $i\in\{1,110\}$. Now $\sigma_{107}=2$ implies that $107|a_ia_{i+107}$ for $i\in\{j:0\le j\le 5\}$, a contradiction. The other cases are excluded similarly.

(*ii*) Let d be even and g be given as in (*ii*). Assume that $k\ge k_0(g)$ and $k-|R|<g$. From (5.2), we have $\prod_{a_i\in R}a_i\ge(2.4)^{|R|}(|R|)!$ whenever $|R|\ge 200$. By taking $i_0=0, h_0=200$, $\mathfrak{m}=\sqrt{k_0(g)}$, $z_1=2.4, \ell=1$, $\mathfrak{n}_0=2^{\frac{1}{3}}, \mathfrak{n}_1=2^{\frac{1}{6}}$ and $\mathfrak{n}_2=1$, we observe that (5.3) and (5.4) are valid for $k\ge g-1+200$. Let $g\in\{33,61,64,128,256,512,1024\}$. Thus (5.3) and (5.4) are valid for $k\ge k_0(g)$. Let $k_1(g)=$

$232, 414, 435, 904, 1907, 4024, 8521$ according as $g = 33, 61, 64, 128, 256, 512, 1024$, respectively. We see that (5.4) is not possible for $k \geq k_1(g)$. Therefore $g \neq 33$ and $k < k_1(g)$. For every k with $k_0(g) \leq k < k_1(g)$, we check that (5.3) is contradicted. Therefore $g \in \{18, 29\}$ and we may assume that $k < 232$. We take $r = 5$ for $101 \leq k < 200$ and $r = 6$ for $200 \leq k < 232$. From (6.10) and (6.6), we get $k - |R| \geq k - F'(k, r) - 2^{r-1}$. We compute that $k - F'(k, r) - 2^{r-1} \geq 18, 29$ for $k \geq 101, 217$, respectively. Hence the assertion (ii) follows.
$(iii), (iv)$ Let g be given as in $(iii), (iv)$. Suppose that $k \geq k_0(g)$ and $k - |R| < g$. We have $\prod_{a_i \in R} a_i \geq (2^\delta)^{|R|-1}(|R| - 1)!$ since $a_i \equiv n (\text{mod } 2^\delta)$. We take $z_1 = 4$ if $4||d$ and $z_1 = 8$ if $8|d$. We observe that (5.3) and (5.4) are valid for $k \geq k_0(g)$ with $i_0 = 1, h_0 = 1$, $\mathfrak{m} = \sqrt{k_0(g)}$, $z_1 = 2 \cdot \ell = 1$, $\mathfrak{n}_0 = 2^{\frac{1}{3}}, \mathfrak{n}_1 = 2^{\frac{1}{6}}$ and $\mathfrak{n}_2 = 1$.

Let $4||d$ and $g \in \{61, 64, 128, 256, 512, 1024\}$. Let $k_1(g) = 288, 306, 640, 1350,$
$2870, 6100$ according as $g = 61, 64, 128, 256, 512, 1024$, respectively. We see that (5.4) is not possible for $k \geq k_1(g)$. Therefore $g \neq 128, 1024$ and $k < k_1(g)$. For every k with $k_0(g) \leq k < k_1(g)$, we check that (5.3) is contradicted.

Let $8|d$ and $g \in \{61, 64, 128, 256, 512, 1024\}$. Let $k_1(g) = 210, 221, 468, 994,$
$2111, 4485$ according as $g = 61, 64, 128, 256, 512, 1024$, respectively. We see that (5.4) is not possible for $k \geq k_1(g)$. Therefore $k < k_1(g)$. For every k with $k_0(g) \leq k < k_1(g)$, we check that (5.3) is contradicted.

Thus we may assume that $g \in \{26, 32, 33\}, k < 286$ if $4||d$ and $g = 33, k < 209$ if $8|d$. By taking $r = 6$ for $101 \leq k < 286$, we get from (6.10) and (6.6) that $k - |R| \geq k - F'(k, r) - 2^{r-\delta} \geq g$ for $k \geq k_0(g)$. Hence the assertions (iii) and (iv) follows.
(v) Let $3|d$. Suppose that $k \geq k_0(g)$ and $k - |R| < g$. We have $\prod_{a_i \in R} a_i \geq 3^{|R|-1}(|R| - 1)!$ since $a_i \equiv n (\text{mod } 3)$. We observe that (5.3) and (5.4) are valid with $i_0 = 1, h_0 = 1, \mathfrak{m} = \sqrt{k_0(g)}$, $z_1 = 3, \ell = 1$, $\mathfrak{n}_0 = 3^{\frac{1}{4}}$, $\mathfrak{n}_1 = 3^{\frac{1}{4}}$ and $\mathfrak{n}_2 = 2^{\frac{1}{6}}$. Let $g \in \{64, 125, 128, 256, 512\}$ and $k_1(g) = 354, 720, 737, 1556, 3300$ according as $g = 64, 125, 128, 256, 512$, respectively. We see that (5.4) is not possible for $k \geq k_1(g)$. Therefore $g \neq 125, 512$ and $k < k_1(g)$. For every k with $k_0(g) \leq k < k_1(g)$, we check that (5.3) is contradicted.

Thus it remains to consider $g \in \{26, 32, 33\}$ and $k < 351$. We take $r = 6$ for $101 \leq k < 351$. We get from (6.10) and (6.13) with $p = 3$ that $k - |R| \geq k - F'(k, r) - 2^{r-2} \geq g$ for $k \geq k_0(g)$.
(vi) Suppose $g \in \{33, 64, 128, 256\}, k \geq k_0(g)$ and $k - |R| < g$. By (ii) and (v), we may assume that $2 \nmid d$ and $3 \nmid d$. We observe that $\prod_{a_i \in R} a_i \geq (\frac{2p}{p-1})^{|R|-\frac{p-1}{2}}(|R| - \frac{p-1}{2})!$ since the number of quadratic residues or quadratic non-residues mod p is $\frac{p-1}{2}$. Let $p|d$ with $p \leq p'$. Then $(\frac{2p}{p-1})^{|R|-\frac{p-1}{2}}(|R| - \frac{p-1}{2})! \geq (\frac{2p'}{p'-1})^{|R|-\frac{p'-1}{2}}(|R| - \frac{p'-1}{2})$. We take $p' = 7, 19$ and 47 in the first, second and third case, respectively. Then (5.3) and (5.4) are valid with $z_1 = \frac{2p'}{p'-1}, i_0 = h_0 = \frac{p'-1}{2}$, $\mathfrak{m} = \sqrt{k_0(g)}, \ell = 1$, $\mathfrak{n}_0 = p'^{\frac{1}{p'+1}}$, $\mathfrak{n}_1 = 5^{\frac{1}{3}}$ and $\mathfrak{n}_2 = 2^{\frac{1}{6}}$. We find that (5.4) is not possible for $k \geq k_0(g) + 24$ and (5.3) is not possible for each k with $k_0(g) \leq k < k_0(g) + 24$. This is a contradiction.
(vii) Let $(z_1, i_0, \ell', \mathfrak{n}'_0, \mathfrak{n}'_1)$ be given by

	$pq\vert d$ $p,q \in \{5,7,11\}$	$2^\delta p\vert d$ $p \in \{3,5\}, \delta \in \{1,3\}$	$105\vert d$	$30\vert d$
(z_1, i_0)	$(\frac{77}{15}, 15)$	$(2^{\delta-1}5, 2)$	$(\frac{35}{2}, 6)$	$(15, 2)$
ℓ'	2	2	3	3
$\mathfrak{n}'_0$	$z_2(7)z_2(11)$	$z_2(2)z_2(5)$	$z_2(3)z_2(5)z_2(7)$	$z_2(2)z_2(3)z_2(5)$
$\mathfrak{n}'_1$	$z_3(5)z_3(7)$	$z_3(2)z_3(3)$	$z_3(3)z_3(5)z_3(7)$	$z_3(2)z_3(3)z_3(5)$
$\mathfrak{n}'_2$	$2^{\frac{1}{6}}$	1	$2^{\frac{1}{6}}$	1

where $z_2(p)=p^{\frac{1}{p+1}}, z_3(p)=p^{\frac{p-1}{2(p+1)}}$. We observe that $\prod_{a_i\in R}a_i\ge z_1^{|R|-i_0}(|R|-i_0)!$ with (z_1,i_0) given above. Suppose $g\in\{256,512\}, k\ge k_0(g)$ and $k-|R|<g$. We see that (5.3) and (5.4) are valid for $k\ge k_0(g)$ with $h_0=i_0$, $\mathfrak{m}=\sqrt{k_0(g)}$, $\ell=\ell'$, $\mathfrak{n}_0=\mathfrak{n}_0', \mathfrak{n}_1=\mathfrak{n}_1'$ and $\mathfrak{n}_2=\mathfrak{n}_2'$. We find that (5.4) is not possible for $k\ge k_0(g)+2$ and (5.3) is not possible for each k with $k_0(g)\le k<k_0(g)+2$. This is a contradiction. □

8. Further Lemmas

We observe that (3.24) is satisfied when $k\ge 11$ by Lemma 4.2. We shall use it without reference in this section.

Lemma 8.1. *Let d be odd and p,q be primes dividing d. Let $\omega(d)\le 4$ and $k\le 821$. Assume that $g_{p,q}(r)\le 2^{r-\omega(d)}$ for $r=5,6$. Then* (1.1) *with $k\ge 101$ has no solution.*

Proof. Suppose equation (1.1) has a solution. Let $r=5$ if $101\le k<257$ and $r=6$ if $257\le k\le 821$. From (6.9), $\nu(a_i)\le 2^{\omega(d)}$ and (6.1), we get $k-F'(k,r)\le\xi_r\le 2^{\omega(d)}g_{p,q}\le 2^r$. We find $k-F'(k,r)>2^r$ by computation. This is a contradiction. □

Lemma 8.2. *Equation* (1.1) *with $k\ge 101$ and $\omega(d)\le 4$ is not possible.*

Proof. We may assume that k is prime by Lemma 7.4. Let d be even. For $k-|R|\ge\mathfrak{h}(5)=4(2^{\omega(d)-\theta}-1)+1$, we get from Corollary 3.10 with $z_0=5$ that $n+(k-1)d<\frac{3}{Q}k^3$ with $Q=32$ if $2||d$ and 16 if $4|d$. Let $\omega(d)\le 3$. Since $k-|R|\ge\mathfrak{h}(5)$ by Lemma 7.6 $(ii),(iii),(iv)$ and $|S_1|\ge\frac{|T_1|}{2^{\omega(d)-\theta}}\ge\frac{0.3k}{2^{3-\theta}}$ by Lemma 4.3, we get $\frac{3}{Q}k^3>n+(k-1)d>2^{\delta}(\frac{0.3k}{2^{3-\theta}}-1)k^2$, a contradiction. Thus $\omega(d)=4$. Let $k\ge 710$. Then $k-|R|\ge\mathfrak{h}(5)$ by Lemma 7.6 and $|S_1|\ge\frac{|T_1|}{2^{\omega(d)-\theta}}\ge\frac{0.4k}{2^{4-\theta}}$ by Lemma 4.3. Hence we get $\frac{3}{Q}>n+(k-1)d>2^{\delta}(\frac{0.4k}{2^{4-\theta}}-1)k^2$, a contradiction again. Therefore $k<710$. By Lemma 7.6, we get $k-|R|\ge\mathfrak{h}(3)$ implying $d<\frac{3}{16}k^2$ if $2||d$ and $d<\frac{3}{4}k^2$ if $4|d$ by Corollary 3.10 with $z_0=3$. However $d\ge 2^{\delta}\cdot 53\cdot 59\cdot 61$ by Lemma 7.5 (c). This is a contradiction.

Thus d is odd. Suppose $|S_1|\le|T_1|-\mathfrak{h}(3)$. By Lemma 3.12, we have

$$d<\frac{\rho}{48}k^2,\ n+(k-1)d<\frac{\rho}{48}k^3. \tag{8.1}$$

Let $k\ge 710$. Since $\nu(a_i)\le 2^{\omega(d)}$, we derive from Lemma 4.3 that $|S_1|\ge\frac{|T_1|}{2^{\omega(d)}}>\frac{0.4k}{16}=0.025k$. Therefore $\max\limits_{A_i\in S_1}A_i>\rho(0.025k-1)$ giving $n+(k-1)d>\rho(0.025k-1)k^2$ which contradicts (8.1). Thus $k<710$. We see from Lemma 4.3 that $|T_1|>0.3k$. For $\omega(d)\le 3$, we have $\max\limits_{A_i\in S_1}A_i>\rho(\frac{0.3k}{8}-1)$ giving $n+(k-1)d>\rho(\frac{0.3k}{8}-1)k^2$ which contradicts (8.1). Let $\omega(d)=4$. By Lemma 7.5 (a), we see that $d\ge$min$(3\cdot 53\cdot 59\cdot 61, 23\cdot 29\cdot 31\cdot 37)>\frac{3}{48}k^2$ contradicting (8.1).

Hence $|S_1|\ge|T_1|-\mathfrak{h}(3)+1$. Therefore

$$n+(k-1)d\ge\rho(|T_1|-\mathfrak{h}(3))k^2. \tag{8.2}$$

Let $k-|R|\ge\mathfrak{h}(5)$. By Corollary 3.10 with $z_0=5$, we get $n+(k-1)d<\frac{3}{16}k^3$ which, together with $|T_1|\ge 0.3k$ by Lemma 4.3, contradicts (8.2) when $\omega(d)\le 2$. Further $k\le 133,275$ when $\omega(d)=3,4$, respectively. Thus either

$$k-|R|<\mathfrak{h}(5) \tag{8.3}$$

or

$$\omega(d) > 2;\ k \le 131 \text{ if } \omega(d) = 3;\ k \le 271 \text{ if } \omega(d) = 4. \tag{8.4}$$

We now apply Lemma 7.6 (i) to get $\omega(d) \ge 2$ and $k \le 293, 487, 991$ for $\omega(d) = 2, 3, 4$, respectively.

Let $3|d$. Then we have from Lemma 7.6 (v) that $\omega(d) > 2$ and $k \le 131, 350$ when $\omega(d) = 3, 4$, respectively. By Lemma 7.5, we get $\mathfrak{p}_2 \ge 53$ and hence $53 \le \mathfrak{p}_2 \le \left(\frac{d}{3}\right)^{\frac{1}{\omega(d)-1}}$. By Corollary 3.10 with $z_0 = 3$ if $\omega(d) = 3$, $z_0 = 2$ if $\omega(d) = 4$ and Lemma 7.6 (v), we get $d < \frac{3}{4}k^2$ if $\omega(d) = 3$ and $< 3k^2$ if $\omega(d) = 4$. Therefore $53 \le \mathfrak{p}_2 < \frac{k}{2} < 67$ if $\omega(d) = 3$ and $53 \le \mathfrak{p}_2 < k^{\frac{2}{3}} \le 350^{\frac{2}{3}} < 53$ if $\omega(d) = 4$. Therefore $\omega(d) = 3$ and $53 \le \mathfrak{p}_2 \le 61$. Now we get a contradiction from Lemma 8.1 with $(p, q) = (3, \mathfrak{p}_2)$ and (6.14).

Thus we may assume that $3 \nmid d$. Therefore $k \le 293, 487, 991$ for $\omega(d) = 2, 3, 4$, respectively, as stated above. Let $\omega(d) = 4$ and $k < 308$. From $k - |R| \ge 9$ by Lemma 7.6 (i) and by Corollary 3.11, there exists a partition (d_1, d_2) of d such that $\max(d_1, d_2) < (k-1)^2$. Thus $\mathfrak{p}_1\mathfrak{p}_2 \le \max(d_1, d_2) < (k-1)^2$ giving $\mathfrak{p}_1 < k-1$. By taking $r = 5$ for $101 \le k < 251$, $r = 6$ for $251 \le k < 308$, we get from (6.10) and $g_{\mathfrak{p}_1} \le 2^{r-1}$ by (6.13) with $p = \mathfrak{p}_1$ that $k - |R| \ge k - F'(k, r) - 2^{r-1} \ge 16$. Now we return to $\omega(d) = 2, 3, 4$. By Lemma 7.6 (i), we get $k - |R| \ge 2^{\omega(d)}$. Then we see from Corollary 3.10 with $z_0 = 2$ that there is a partition (d_1, d_2) of d with $d_1 < k - 1, d_2 < 4(k - 1)$. Thus $\mathfrak{p}_1 < k$. We take $r = 5$ for $101 \le k < 211$ and $r = 6$ for $211 \le k < 556$ for the next computation and we use Lemma 7.6 (i) for $k \ge 556$. From (6.10) with $p = q = \mathfrak{p}_1$ and (6.13) with $p = \mathfrak{p}_1$, and since $\sum_{p|d,p>p_r} \sigma_p - g_{\mathfrak{p}_1} \ge 2 - 2^{r-1}$ if $\mathfrak{p}_1 > p_r$ and $\ge -2^{r-2}$ if $\mathfrak{p}_1 \le p_r$, we get

$$k - |R| \ge k - F'(k, r) + 2 - 2^{r-1} \ge \begin{cases} 20 & \text{for } k \ge 101 \\ 29 & \text{for } k \ge 211 \\ 33 & \text{for } k \ge 251. \end{cases} \tag{8.5}$$

Therefore we get from (8.3), (8.4) that $\omega(d) > 2$ and $k \le 199, 991$ when $\omega(d) = 3, 4$, respectively.

Let $\omega(d) = 3$. By Corollary 3.10 with $z_0 = 3$, there is a partition (d_1, d_2) with $d_1 < \frac{k-1}{2}$ and $d_2 < 2(k-1)$. Thus $\mathfrak{p}_1\mathfrak{p}_2 \le \max(d_1, d_2) < 2(k - 1)$ giving $\mathfrak{p}_1 < \sqrt{2(k-1)} \le \sqrt{2 \cdot 198}$ and hence $p_1 \le 19$. Further the possibility $p_1 = 19$ is excluded since $19 \cdot 23 > 2(k - 1)$. Also $\mathfrak{p}_2 \le 79, 53, 31, 29, 23$ for $\mathfrak{p}_1 = 5, 7, 11, 13, 17$, respectively. Now we apply Lemma 7.5 (a) to derive that either $\mathfrak{p}_1 = 5, 53 \le \mathfrak{p}_2 \le 79$ or $\mathfrak{p}_1 = 7, \mathfrak{p}_2 = 53$. Further from $5 \cdot 53 < 2(k - 1)$, we get $k \ge 134$. Thus $k - |R| \le 28$ by (8.3) and (8.4). Now we take $r = 6$ for $134 \le k \le 199$ in the next computation. We get from (6.10) and (6.14) with $(p, q) = (\mathfrak{p}_1, \mathfrak{p}_2)$ that $k - |R| \ge k - F'(k, r) - 2^{r-2} \ge 29$. This is a contradiction.

Let $\omega(d) = 4$. By Lemma 7.5 $(a), (b)$, we get $d \ge \min(5 \cdot 53 \cdot 59 \cdot 61, 23 \cdot 47 \cdot 53 \cdot 59, 31 \cdot 41 \cdot 47 \cdot 53) = 953735$. Further by Corollary 3.10 with $z_0 = 2$ if $k < 251$, $z_0 = 3$ if $k \ge 251$ and (8.5), we obtain $d < 3k^2$ if $k < 251$ and $d < \frac{3}{4}k^2$ for $k \ge 251$. This is a contradiction since $k \le 991$. $\square$

Lemma 8.3. *Assume* (1.1) *with* $\omega(d) \ge 12$. *Suppose that*

$$d < \frac{3}{16}k^2, n + (k-1)d < \frac{3}{16}k^3. \tag{8.6}$$

Then $k < \omega(d)4^{\omega(d)}$.

Proof. Assume that $k \ge \omega(d)4^{\omega(d)}$. Then from $40 \cdot \left(\frac{3}{16}\right)^{\frac{2}{11}} < (12)^{\frac{7}{11}}2^{\frac{36}{11}}$ and $\omega(d) \ge 12$, we get $\left(\frac{3k^2}{16}\right)^{\frac{2}{11}} \le \frac{k}{40 \cdot 2^{\omega(d)}}$. This together with $\mathfrak{q}_1\mathfrak{q}_2 \le \left(\frac{d}{2^{\delta\theta}}\right)^{\frac{2}{\omega(d)-\theta}} < \left(\frac{3k^2}{16}\right)^{\frac{2}{11}}$ by (2.9) and (8.6) gives $\mathfrak{q}_1\mathfrak{q}_2 < \frac{k}{40 \cdot 2^{\omega(d)}}$. Hence we derive from Corollary 3.7 (ii) with $d'=\mathfrak{q}_1\mathfrak{q}_2$ that

$$\nu(A_i)\le 2^{\omega(d)-2-\theta} \text{ whenever } A_i\ge \frac{k}{40\cdot 2^{\omega(d)}}. \tag{8.7}$$

Let

$$T^{(1)}=\{i\in T_1 : A_i>\frac{2^{\delta}\rho k}{6\cdot 2^{\omega(d)}}\},\ T^{(2)}=T_1\setminus T^{(1)} \tag{8.8}$$

and

$$S^{(1)}=\{A_i : i\in T^{(1)}\},\ S^{(2)}=\{A_i : i\in T^{(2)}\}. \tag{8.9}$$

Then considering residue classes modulo $2^{\delta}\rho$, we derive that

$$\frac{2^{\delta}\rho k}{6\cdot 2^{\omega(d)}}\ge \max_{A_i\in S^{(2)}} A_i\ge 2^{\delta}\rho(|S^{(2)}|-1)+1$$

so that $|S^{(2)}|\le \frac{k}{6\cdot 2^{\omega(d)}}+1\le \frac{k}{6\cdot 2^{\omega(d)}}+1$. We have from (8.8), (8.9) and (8.7) together with $\nu(A_i)\le 2^{\omega(d)}$ by Corollary 3.7 (ii) that

$$\begin{aligned}|T^{(2)}|&\le \frac{k}{40\cdot 2^{\omega(d)}}2^{\omega(d)}+\left(\frac{k}{6\cdot 2^{\omega(d)}}-\frac{k}{40\cdot 2^{\omega(d)}}+1\right)2^{\omega(d)-2}\\ &\le \frac{k}{40}+\frac{1}{4}\left(\frac{k}{6}-\frac{k}{40}\right)+2^{\omega(d)-2}\le \frac{k}{24}+\frac{3k}{160}+\frac{k}{480}=\frac{k}{16}\end{aligned}$$

since $k\ge \omega(d)4^{\omega(d)}$ and $\omega(d)\ge 12$. By Lemma 4.3 and $k>1639$, we have

$$|T^{(1)}|>|T_1|-|T^{(2)}|\ge 0.42k-\frac{k}{16}=0.3575k.$$

Let $\mathfrak{C}$, $\mathfrak{C}_\mu$ be as in Lemma 5.5 with $c=2$. Then $.3575k<|T^{(1)}|=|S^{(1)}|+\sum_{\mu\ge 2}(\mu-1)|\mathfrak{C}_\mu|\le |S^{(1)}|+\mathfrak{C}\le |S^{(1)}|+\frac{3\log 2}{16}\omega(d)4^{\omega(d)}$ by Lemma 5.5. Now we use $\frac{3\log 2}{16}<\frac{1}{7.6}$ to get $0.3575k<|S^{(1)}|+\frac{k}{7.6}$ implying $|S^{(1)}|>0.2259k$. Therefore $n+(k-1)d\ge (\max_{A_i\in S^{(1)}} A_i)k^2\ge 0.2259k^3$ contradicting (8.6). ☐

Lemma 8.4. *Assume* (1.1) *with* $\omega(d)\ge 5$. *Then there is no non-degenerate double pair.*

Proof. Assume (1.1) with $\omega(d)\ge 5$. Further we suppose that there exists a non-degenerate double pair. Then we derive from Lemma 3.4 with $z_0=2$ that

$$d<\mathcal{X}_0k^2,\ n+(k-1)d<\mathcal{X}_0k^3 \tag{8.10}$$

where

$$\mathcal{X}_0=3,\frac{3}{2},12,6 \text{ if } 2\nmid d, 2||d, 4||d, 8|d, \text{ respectively.} \tag{8.11}$$

This with $d\ge 2^{\delta}\prod_{i=2}^{\omega(d)+1-\delta'}p_i$ implies $k^2>\frac{1}{6}\prod_{i=1}^{\omega(d)}p_i$. Therefore we get from Lemma 5.1 $(ii),(iv)$ that

$$\log(\frac{k}{\omega(d)2^{\omega(d)}})\ge \omega(d)\left\{\frac{\log\omega(d)+\log\log\omega(d)-1.076868}{2}-\log 2-\frac{\log\omega(d)}{\omega(d)}\right\}-\frac{\log 6}{2}.$$

The right side of the above inequality is an increasing function of $\omega(d)$ and hence $k>9\omega(d)2^{\omega(d)}$ for $\omega(d)\ge 12$. We find from $\mathcal{X}_0k^2>d\ge 2^{\delta}\prod_{i=2}^{\omega(d)+1-\delta'}p_i$ that $k>3.2\omega(d)2^{\omega(d)}$ if $\omega(d)=10,11$. Further $k>2.97\omega(d)2^{\omega(d)}$ if $\omega(d)=8,9$ when d is odd. Also $k>2542, 12195$ when $\omega(d)=8,9$, respectively if $2||d$ or $8|d$ and $k>1271, 6097$ when $\omega(d)=8,9$, respectively if $4||d$.

Suppose $k<1733$. Then $\omega(d)\le 8$ if $4||d$ and $\omega(d)<8$ otherwise. By Lemma 7.5 (a), (c), we get $d\ge$min$(3\cdot 53\cdot 59\cdot 61\cdot 67, 23\cdot 29\cdot 31\cdot 37\cdot 41)$ if d is odd and $d\ge 2^{\delta}\cdot 53\cdot 59\cdot 61\cdot 67$ if d is even. This is not possible since $d<\mathcal{X}_0k^2$. Hence $k\ge 1733$.

Let d be even and $\omega(d) = 8, 9$. Since $k \geq 1733$, we get $k - |R| \geq \mathfrak{h}(3)$ by Lemma 7.6 $(ii), (iii), (iv)$ implying $d < \frac{3}{16}k^2$, $\frac{3}{4}k^2$ if $2||d$, $4|d$, respectively, by Corollary 3.10 with $z_0 = 3$. Therefore $k \geq 2.48\omega(d)2^{\omega(d)}$ if $4||d$ and $k \geq 3.2\omega(d)2^{\omega(d)}$ otherwise.

Therefore for $\omega(d) \geq 8$, we have

$$k \geq \begin{cases} 2.48\omega(d)2^{\omega(d)} & \text{if } 4||d \\ 2.97\omega(d)2^{\omega(d)} & \text{if } d \text{ is odd}, \ \omega(d) = 8, 9 \\ 3.2\omega(d)2^{\omega(d)} & \text{otherwise} \end{cases} \tag{8.12}$$

Suppose that $|S_1| \leq |T_1| - \mathfrak{h}(3)$ if d is odd and $|S_1| \leq |T_1| - \mathfrak{h}(5)$ if d is even. We put

$$\mathcal{X} := \begin{cases} \frac{\rho}{48} & \text{if } \mathrm{ord}_2(d) \leq 1 \\ \frac{1}{12} & \text{if } \mathrm{ord}_2(d) \geq 2, 3 \nmid d \\ \frac{3}{16} & \text{if } \mathrm{ord}_2(d) \geq 2, 3|d. \end{cases}$$

Then

$$d < \mathcal{X}k^2, n + (k-1)d < \mathcal{X}k^3 \tag{8.13}$$

by Lemma 3.12. Therefore $k < \omega(d)4^{\omega(d)}$ for $\omega(d) \geq 12$ by Lemma 8.3.

Let $\omega(d) \geq 19$. Then

$$\left(2^\delta \prod_{i=2}^{9} p_i\right)(29)^{\omega(d)-8-\delta'} \leq d < \mathcal{X}k^2 < W := \begin{cases} \frac{3}{48}\omega(d)^2(16)^{\omega(d)} & \text{if } \mathrm{ord}_2(d) \leq 1 \\ \frac{3}{16}\omega(d)^2(16)^{\omega(d)} & \text{if } \mathrm{ord}_2(d) \geq 2. \end{cases}$$

Therefore

$$\frac{29}{16} < \left(\left(64\prod_{i=3}^{9} p_i\right)^{-1} 29^9\omega(d)^2\right)^{\frac{1}{\omega(d)}}.$$

We see that the right hand side of the above inequality is a non-increasing function of $\omega(d)$ and the inequality does not hold at $\omega(d) = 26$. Thus $\omega(d) \leq 25$. Further we get a contradiction from $2^\delta \prod_{i=2}^{\omega(d)+1-\delta'} p_i \leq d < W$ since $\omega(d) \geq 19$.

Thus $\omega(d) \leq 18$. We get from (2.9) and $d < \mathcal{X}k^2$ that

$$\mathfrak{q}_1 \cdots \mathfrak{q}_h < \mathcal{X}_1^h := \begin{cases} \left(\frac{\rho}{48}\right)^{\frac{h}{\omega(d)}} k^{\frac{2h}{\omega(d)}} & \text{if } d \text{ is odd} \\ \left(\frac{\rho}{96}\right)^{\frac{h}{\omega(d)-1}} k^{\frac{2h}{\omega(d)-1}} & \text{if } 2||d \\ \left(\frac{1}{12\cdot 4^\theta}\right)^{\frac{h}{\omega(d)-\theta}} k^{\frac{2h}{\omega(d)-\theta}} & \text{if } 4|d, 3 \nmid d \\ \left(\frac{3}{16\cdot 4^\theta}\right)^{\frac{h}{\omega(d)-\theta}} k^{\frac{2h}{\omega(d)-\theta}} & \text{if } 4|d, 3|d \end{cases}$$

for $1 \leq h \leq \omega(d) - \theta$. Further from $\mathcal{X}k^2 > d \geq 2^\delta \mathfrak{p}_1 \cdots \mathfrak{p}_{\omega(d)-\delta'}$, we get

$$k > k_1 := \begin{cases} \sqrt{\frac{2^\delta}{\mathcal{X}} \prod_{i=2}^{\omega(d)+1-\delta'} p_i} & \text{if } 3|d \\ \sqrt{\frac{2^\delta}{\mathcal{X}} \prod_{i=3}^{\omega(d)+2-\delta'} p_i} & \text{if } 3 \nmid d. \end{cases}$$

Thus

$$k > k_2 := \max(1733, k_1) \tag{8.14}$$

Further we derive from (8.13) that

$$\frac{\mathfrak{p}_1 - 1}{2} \cdots \frac{\mathfrak{p}_h - 1}{2} < \mathcal{X}_2^h := \begin{cases} \frac{1}{2^{h-1}}\left(\frac{\mathcal{X}k^2}{3\cdot 2^\delta}\right)^{\frac{h-1}{\omega(d)-1-\delta'}} & \text{if } 3|d \\ \frac{1}{2^h}\left(\frac{\mathcal{X}k^2}{2^\delta}\right)^{\frac{h}{\omega(d)-\delta'}} & \text{if } 3 \nmid d \end{cases}$$

for $1\le h\le \omega(d)-\delta'$.

We take $r=[\frac{\omega(d)-1}{2}]$ if d is odd and $r=[\frac{\omega(d)}{2}]-1$ if d is even. By Corollary 3.8 and $|T_1|>0.42k$ by Lemma 4.3, we have

$$s_{r+1}\ge \frac{0.42k}{2^{\omega(d)-r-\theta}}-2\lambda_r-2^{r-1}\lambda_1-\sum_{\mu=2}^{r-1}2^{r-\mu}\lambda_\mu. \tag{8.15}$$

This with Corollary 4.5 and $\mathfrak{q}_1\mathfrak{q}_2\cdots\mathfrak{q}_h<\mathcal{X}_1^h$ gives (8.13) gives

$$s_{r+1}\ge\mathcal{X}_3:=\begin{cases}\frac{0.42k}{2^{\omega(d)-r}}-\frac{\mathcal{X}_1^r}{3\cdot 2^{r-3}}-\sum_{\mu=1}^{r-1}\frac{2^{r+2}}{3}\frac{\mathcal{X}_1^\mu}{2^{2\mu}} & \text{if } 2\nmid d, 3\nmid d\\ \frac{0.42k}{2^{\omega(d)-\theta-r}}-\frac{\mathcal{X}_1^r}{3\cdot 2^{r-4+\delta}}-2^{r-1}(\frac{\mathcal{X}_1}{2^\delta}+1)-\sum_{\mu=2}^{r-1}\frac{2^{r+3-\delta}}{3}\frac{\mathcal{X}_1^\mu}{2^{2\mu}} & \text{if } 2|d, 3\nmid d\\ \frac{0.42k}{2^{\omega(d)-\theta-r}}-\frac{\mathcal{X}_1^r}{9\cdot 2^{r-4+\delta'}}-2^{r-1}(\frac{\mathcal{X}_1}{3\cdot 2^\delta}+1)-\sum_{\mu=2}^{r-1}\frac{2^{r+3-\delta'}}{9}\frac{\mathcal{X}_1^\mu}{2^{2\mu}} & \text{if } 3|d, 8\nmid d\\ \frac{0.42k}{2^{\omega(d)-r}}-2(\frac{\mathcal{X}_1^r}{24}+1)-\sum_{\mu=1}^{r-1}2^{r-\mu}(\frac{\mathcal{X}_1^\mu}{24}+1) & \text{if } 8|d, 3|d, r\le 3\\ \frac{0.42k}{2^{\omega(d)-r}}-\frac{\mathcal{X}_1^r}{9\cdot 2^{r-3}}-\sum_{\mu=1}^{3}2^{r-\mu}(\frac{\mathcal{X}_1^\mu}{24}+1)-\sum_{\mu=4}^{r-1}\frac{2^{r+2}}{9}\frac{\mathcal{X}_1^\mu}{2^{2\mu}} & \text{if } 8|d, 3|d, r\ge 4.\end{cases}$$

By observing that $\frac{\mathcal{X}_3-\mathcal{X}_2^r}{k}$ is an increasing function of k and is positive at $k=k_2$ except when $\omega(d)=7, d$ odd and $3|d$ in which case it is positive at $k=11500$. Let $k\ge 25500$ when $\omega(d)=7, d$ odd and $3|d$. Then $s_{r+1}\ge\mathcal{X}_3>\mathcal{X}_2^r>\frac{\mathfrak{p}_1-1}{2}\cdots\frac{\mathfrak{p}_r-1}{2}$. Therefore by Lemma 4.4 with $S=\{A_i: i\in T_{r+1}\}, |S|=s_{r+1}, h=r$ and (8.13), we get

$$\mathcal{X}k^3>n+(k-1)d\ge\mathcal{X}_4k^2:=\begin{cases}\frac{3}{4}2^{r+\delta}\mathcal{X}_3k^2 & \text{if } 3\nmid d\\ \frac{9}{4}2^{r+\delta-1}\mathcal{X}_3k^2 & \text{if } 3|d.\end{cases}$$

This is a contradiction by checking that $\frac{\mathcal{X}_4}{k}-\mathcal{X}>0$ except when d odd, $3|d$ and $\omega(d)=6,8,9$. Thus we may assume that d is odd, $3|d, 6\le\omega(d)\le 9$ and $k<25500$ if $\omega(d)=7$. Also we check that $\frac{\mathcal{X}_4}{k}-\mathcal{X}>0$ for $k=5000, 62000, 350000$ according as $\omega(d)=6,8,9$, respectively. Thus we may assume that $k<5000, 25500, 62000, 350000$ whenever $\omega(d)=6,7,8,9$, respectively. If $\mathfrak{q}_1\ge 7$, then we get a contradiction from $d<\mathcal{X}k^2=\frac{1}{16}k^2$ and $\frac{d}{7\cdot 9\cdot 11\cdot 13\cdot 17\cdot 19}\ge 1, 23, 23\cdot 25, 23\cdot 25\cdot 29$ for $\omega(d)=6,7,8,9$, respectively. Thus $\mathfrak{q}_1\in\{3,5\}$. Further we get $\mathfrak{q}_1\le 5, \mathfrak{q}_2\le 7$ if $\omega(d)=6$, $\mathfrak{q}_1\le 5, \mathfrak{q}_2\le 7, \mathfrak{q}_3\le 11$ if $\omega(d)=7,8$ and $\mathfrak{q}_1=3, \mathfrak{q}_2=5, \mathfrak{q}_3=7$ if $\omega(d)=9$. Thus $\mathfrak{p}_1=3$ and $\mathfrak{p}_2\in\{5,7\}$ if $\omega(d)=6$, $\mathfrak{p}_2, \mathfrak{p}_3\in\{5,7,11\}$ if $\omega(d)>6$. Since $\left(\frac{a_i}{p}\right)=\left(\frac{n}{p}\right)$ for $p|d$, we consider Legendre symbols modulo $3, \mathfrak{q}_1, \mathfrak{q}_2$ to all squarefree positive integers $\le\mathfrak{q}_1$ and $\le\mathfrak{q}_1\mathfrak{q}_2$ to obtain $\lambda_1\le 1, \lambda_2\le 3$. Further for $\omega(d)>6$, we consider Legendre symbols modulo $3, \mathfrak{q}_1, \mathfrak{q}_2$ and $\mathfrak{q}_3$ if $\mathfrak{q}_3\ne 9$ to all squarefree positive integers $\le\mathfrak{q}_1\mathfrak{q}_2\mathfrak{q}_3$ to get $\lambda_3\le 17$. Therefore we get from (8.15) and Corollary 4.5 that

$$s_{r+1}\ge\mathcal{X}_5:=\begin{cases}\frac{0.42k}{2^4}-8 & \text{if } \omega(d)=6\\ \frac{0.42k}{2^{\omega(d)-3}}-44 & \text{if } \omega(d)=7,8\\ \frac{0.42k}{2^5}-\frac{1}{9}\left(\frac{1}{16}\right)^{\frac{4}{9}}k^{\frac{8}{9}}-54 & \text{if } \omega(d)=9.\end{cases}$$

We check that $s_{r+1}\ge\mathcal{X}_5>\mathcal{X}_2^r>\frac{\mathfrak{p}_1-1}{2}\cdots\frac{\mathfrak{p}_r-1}{2}$ by observing $\frac{\mathcal{X}_5-\mathcal{X}_2^r}{k}$ is an increasing function of k and is positive at $k=$max$(1733, k_1)$. Therefore by Lemma 4.4 with $h=r$ and (8.13), we get $\frac{1}{16}k^3>n+(k-1)d\ge\frac{9}{8}2^r\mathcal{X}_5k^2$. This is a contradiction since $\frac{\mathcal{X}_5}{k}-\frac{1}{18\cdot 2^r}>0$.

Thus $|S_1|\ge\mathcal{X}_6$ using $|T_1|>0.42k$ by Lemma 4.3 where $\mathcal{X}_6=0.42k-\mathfrak{h}(3)+1$ if d is odd and $\mathcal{X}_6=0.42k-\mathfrak{h}(5)+1$ if d is even. Since there exists a non-degenerate double pair, we apply Lemma 3.4 with

$z_0 = 2$ to get a partition (d_1, d_2) of d with

$$\begin{cases} \mathfrak{p}_1\mathfrak{p}_2\cdots\mathfrak{p}_{[\frac{\omega(d)+1}{2}]} \le \max(d_1,d_2) < 4k & \text{if } 2\nmid d \\ \mathfrak{p}_1\mathfrak{p}_2\cdots\mathfrak{p}_{[\frac{\omega(d)}{2}]} \le \max(d_1,d_2) < 4k & \text{if } 2||d \\ 2\mathfrak{p}_1\mathfrak{p}_2\cdots\mathfrak{p}_{[\frac{\omega(d)}{2}]} \le \max(d_1,d_2) < 8k & \text{if } 4|d. \end{cases}$$

Let $\omega(d) \ge 7+\delta'$. Then we see from (8.12) that $|S_1| \ge \mathcal{X}_6 > \frac{k}{4} > \frac{\mathfrak{p}_1-1}{2}\cdots\frac{\mathfrak{p}_4-1}{2}$. We now apply Lemma 4.4 with $h=4$ to get $\mathcal{X}_0 k > n+(k-1)d \ge \frac{3}{4}2^{4+\delta}\mathcal{X}_6 k^2 > 3\cdot 2^{\delta}k^3$ since $\mathcal{X}_6 > \frac{k}{4}$. This contradicts (8.11). Thus $\omega(d) \le 6+\delta'$ and $k \ge 1733$ by (8.12).

Assume that $k-|R| \ge \mathfrak{h}(3)$. Then from Corollary 3.10 with $z_0 = 3$, we get $n+(k-1)d < \mathcal{X}_7 k^3$ where $\mathcal{X}_7 = \frac{3}{16}$ if $2||d$ and $\frac{3}{4}$ otherwise. If $2|d$ or $3|d$, then $n+(k-1)d \ge 3(\mathcal{X}_6-1)k^2$ if $3|d$ and $n+(k-1)d \ge 2^{\delta}(\mathcal{X}_6-1)k^2$ if $2|d$ contradicting $n+(k-1)d < \mathcal{X}_7 k^3$. Thus d is odd, $3\nmid d$ and $\omega(d) = 5, 6$. By Corollary 3.10 with $z_0 = 3$, there is a partition (d_1, d_2) of d with $\mathfrak{p}_1\mathfrak{p}_2\mathfrak{p}_3 \le$max$(d_1,d_2) < 2(k-1)$. Now we get $\frac{k}{4} > \frac{\mathfrak{p}_1-1}{2}\frac{\mathfrak{p}_2-1}{2}\frac{\mathfrak{p}_3-1}{2}$. Further we check $\mathcal{X}_6 > \frac{k}{4}$ implying $|S_1| \ge \mathcal{X}_6 > \frac{\mathfrak{p}_1-1}{2}\frac{\mathfrak{p}_2-1}{2}\frac{\mathfrak{p}_3-1}{2}$. Therefore we derive from Lemma 4.4 with $h = 3$ that $\frac{3}{4}k^3 = \mathcal{X}_7 k^3 > n+(k-1)d \ge 6X_6 k^2 > \frac{3}{2}k^3$, a contradiction. Hence $k-|R| < \mathfrak{h}(3)$. By Lemma 7.6 $(i)-(iv)$, we get d odd, $\omega(d) = 6$ and $1733 \le k < 2082$. Further from Lemma 7.6 $(v), (vi)$, we get $\mathfrak{p}_1 \ge 11$. Now $11\cdot 13\cdot 17\cdot 19\cdot 23\cdot 29 \le d < 3k^2$ by (8.10) and (8.11). This is a contradiction. □

Corollary 8.5. *Equation* (1.1) *with* $\omega(d) \ge 5$ *implies that* $k-|R| < 2^{\omega(d)-\theta}$.

Proof. Assume (1.1) with $\omega(d) \ge 5$ and $k-|R| \ge 2^{\omega(d)-\theta}$. By Lemma 3.9, there exists a set Ω with at least $2^{\omega(d)-\theta}$ pairs satisfying *Property ND*. Since there are at most $2^{\omega(d)-\theta}-1$ permissible partitions of d by Lemma 3.5 (i), we can find a partition (d_1, d_2) of d and a non-degenerate double pair with respect to (d_1, d_2). This contradicts Lemma 8.4. □

Lemma 8.6. *Equation* (1.1) *with d odd,* $k \ge 101$ *and* $5 \le \omega(d) \le 7$ *implies that* $k-|R| \le 2^{\omega(d)-1}$.

Proof. Let d be odd. Assume (1.1) with $5 \le \omega(d) \le 7$ and $k-|R| \ge 2^{\omega(d)-1}+1$. By Corollary 8.5, we may suppose that $k-|R| < 2^{\omega(d)}$. Further by Lemma 7.6 (i), we obtain $k \le 555, 1056, 2099$ when $\omega(d) = 5, 6, 7$, respectively. Since $k-|R| \ge 2^{\omega(d)-1}+1$, we derive from Corollary 3.11 that there exists a partition (d_1, d_2) of d such that $\mathfrak{D}_{12}$:=max$(d_1,d_2) < (k-1)^2$.

Let $\omega(d) = 5$. Then $\mathfrak{p}_1\mathfrak{p}_2\mathfrak{p}_3 \le \mathfrak{D}_{12} < (k-1)^2$ implying $\mathfrak{p}_1 \le 61$ since $67\cdot 71\cdot 73 > 555^2$. Also $\mathfrak{p}_2 < \frac{k-1}{\sqrt{\mathfrak{p}_1}}$. By taking $r = 6$ for $208 < k \le 547$, we get from (6.10) and (6.13) with $p = \mathfrak{p}_1$ that $k-|R| \ge k-F'(k,r)+\min(-2^{r-2}, \sigma_{61}-2^{r-1}) \ge 32$ if $k > 208$. Thus $k \le 208$. Further $\mathfrak{p}_1 \le 29$ since $31\cdot 37\cdot 41 > 208^2$. If $\mathfrak{p}_1 \ge 17$, then we obtain from Lemma 7.5 $(a), (b)$ that $207^2 > \mathfrak{D}_{12} \ge$min$(17\cdot 53\cdot 59, 23\cdot 47\cdot 53)$, a contradiction. Therefore $\mathfrak{p}_1 \le 13$ and hence $53 \le \mathfrak{p}_2 < k$ by Lemma 7.5 (a). By taking $r = 6$, we get from (6.14) with $(p,q) = (\mathfrak{p}_1, \mathfrak{p}_2)$ that $g_{\mathfrak{p}_1,\mathfrak{p}_2} = 2^{r-3}$ if $k \le 127$ and $g_{\mathfrak{p}_1} = 2^{r-2}$ if $k > 127$ by (6.13) with $p = \mathfrak{p}_1$. From (6.10) and $\sigma_{\mathfrak{p}_2} \ge 2$, we have $k-|R| \ge k-F'(k,r)+2-2^{r-3}$ if $k \le 127$ and $k-|R| \ge k-F'(k,r)+2-2^{r-2}$ if $k > 127$ giving $k-|R| \ge 32$, a contradiction.

Let $\omega(d) = 6$. Then $\mathfrak{p}_2\mathfrak{p}_3\mathfrak{p}_4 \le \mathfrak{D}_{12} < (k-1)^2$ implying $\mathfrak{p}_1 < \mathfrak{p}_2 \le 97$ since $101\cdot 103\cdot 107 > 1055^2$. By taking $r = 7$ for $384 < k \le 1039$, we get from (6.10) and (6.14) with $(p,q) = (\mathfrak{p}_1, \mathfrak{p}_2)$ that $k-|R| \ge k-F'(k,r)-2^{r-2} \ge 64$ if $k > 384$. Thus $k \le 384$. Further $\mathfrak{p}_2 \le 43$ since $47\cdot 53\cdot 59 > 383^2$. Then we derive from Lemma 7.5 $(a), (b)$ that $\mathfrak{p}_1 = 31, \mathfrak{p}_2 = 41, \mathfrak{p}_3 \ge 47$. Also $k > 319$ since $41\cdot 47\cdot 53 > 319^2$. By taking $r=7$ for $319<k\le 384$, we obtain from (6.10) and (6.14) with $(p,q)=(31,41)$ that $k-|R|\ge k-F'(k,r)+\sigma_{31}+\sigma_{41}-2^{r-2}\ge 64$. This is a contradiction.

Let $\omega(d)=7$. Suppose $\mathfrak{p}_1\le 19$. By Lemma 7.6 $(v),(vi),vii)$, we get $k<735,930,1200$ according as $\mathfrak{p}_1=3,\mathfrak{p}_1\in\{5,7\},\mathfrak{p}_1\ge 11$, respectively. By Lemma 7.5 (a), we obtain $\mathfrak{p}_2\ge 53$. Now $53\cdot 59\cdot 61\le \frac{\mathfrak{D}_{12}}{\mathfrak{p}_1}<\frac{735^2}{3},\frac{930^2}{5},\frac{1200^2}{11}$ according as $\mathfrak{p}_1=3,\mathfrak{p}_1\in\{5,7\},\mathfrak{p}_1\ge 11$, respectively. This is not possible. Thus $\mathfrak{p}_1\ge 23$. Further $\mathfrak{p}_1\le 41,\mathfrak{p}_2\le 53$ from $\mathfrak{p}_1\mathfrak{p}_2\mathfrak{p}_3\mathfrak{p}_4\le\mathfrak{D}_{12}<(k-1)^2\le 2098^2$. By taking $r=9$, we get from (6.10) and (6.14) with $(p,q)=(\mathfrak{p}_1,\mathfrak{p}_2)$ that $k-|R|\ge k-F'(k,r)+\min(-2^{r-3}+\sigma_{53},-2^{r-2}+\sigma_{41}+\sigma_{53})\ge 128$ for $k>1007$. Therefore $k\le 1007$. Now $1007^2>\mathfrak{D}_{12}\ge\min(23\cdot 47\cdot 53\cdot 59,31\cdot 41\cdot 47\cdot 53)$ by Lemma 7.5 (b). This is not possible. $\square$

Corollary 8.7. *Assume* (1.1) *with* $\omega(d)\ge 5$. *Then* $k<308,556,1057,2870$ *and* $2(\omega(d)-\theta)2^{\omega(d)-\theta}$ *for* $\omega(d)=5,6,7,8$ *and* ≥ 9, *respectively. In particular* $k<2\omega(d)2^{\omega(d)}$.

Proof. By Corollary 8.5 and Lemma 8.6, we derive that $k-|R|<2^{\omega(d)-\theta}$ and $k-|R|\le 2^{\omega(d)-1}$ if d is odd, $5\le\omega(d)\le 7$. By Lemma 7.6 $(i),(ii)$, we get $k<2(\omega(d)-\theta)2^{\omega(d)-\theta}$ for $\omega(d)\ge 9+\theta$, $k<4252$ if $\omega(d)=8$ and $k<308,556,1057$ according as $\omega(d)=5,6,7$, respectively. Now it remains to consider $\omega(d)=9$ if $2||d,4||d$ and $\omega(d)=8$. By Lemma 7.6 (ii), it suffices to consider d odd and $\omega(d)=8$. Further $k<4252$ and $k-|R|<256$. Suppose $k\ge 2870$. Then $k-|R|\ge 129$ by Lemma 7.6 (i) and we derive from Corollary 3.11 that there exists a partition (d_1,d_2) of d with $\max(d_1,d_2)<(k-1)^2$. Let $\mathfrak{p}_1\ge 53$. Then $4252^4>d\ge 53\cdot 59\cdot 61\cdot 67\cdot 71\cdot 73\cdot 79\cdot 83$, a contradiction. Thus $\mathfrak{p}_1\le 47$. Now we obtain from Lemma 7.6 (vi) that $k-|R|\ge 256$, a contradiction. $\square$

Lemma 8.8. (i) *Let d be odd and $\omega(d)=5,6$. Suppose that d is divisible by a prime $\le k$ when $\omega(d)=5$. Further assume that there exist distinct primes p and q with $pq|d$, $p\le 19,q\le k$ when $\omega(d)=6$. Then* (1.1) *with $k\ge 101$ has no solution.*
(ii) *Let d be even and $5\le\omega(d)\le 6+\theta$. Assume that $p|d$ with $p\le 47$ when $\omega(d)=7$. Then* (1.1) *with $k\ge 101$ has no solution.*

Proof. By Lemma 8.5, we may suppose that $k-|R|<2^{\omega(d)-\theta}$.

(i) Let d be odd. From Corollary 8.7, we get $k<308,556$ when $\omega(d)=5,6$, respectively. Let $\omega(d)=5$. By taking $r=5$ for $101\le k<308$, we get from (6.10) and (6.13) with $p=\mathfrak{p}_1$ that $k-|R|\ge k-F'(k,r)-2^{r-1}\ge 17$ which is not possible by Lemma 8.6.

Let $\omega(d)=6$. Then $53\le\mathfrak{p}_2\le k$ by Lemma 7.5 (a). We take $r=6$. Let $\mathfrak{p}_1\le 13$. Then we get from (6.14) with $(p,q)=(\mathfrak{p}_1,\mathfrak{p}_2)$ that $g_{\mathfrak{p}_1,\mathfrak{p}_2}=2^{r-3}$ if $k\le 127$ and $g_{\mathfrak{p}_1}=2^{r-2}$ if $k>127$ by (6.13) with $p=\mathfrak{p}_1$. From (6.10) and $\sigma_{\mathfrak{p}_2}\ge 1$, we have $k-|R|\ge k-F'(k,r)+1-2^{r-3}$ if $k\le 127$ and $k-|R|\ge k-F'(k,r)+1-2^{r-2}$ if $k>127$ giving $k-|R|\ge 33$. This contradicts Lemma 8.6. Thus $\mathfrak{p}_1\in\{17,19\}$. We get from (6.14) with $(p,q)=(\mathfrak{p}_1,\mathfrak{p}_2)$ that $g_{\mathfrak{p}_1,\mathfrak{p}_2}=2^{r-2}$ if $k\le 193$ and $g_{\mathfrak{p}_1}=2^{r-1}$ if $k>193$ by (6.13) with $p=\mathfrak{p}_1$. From (6.10) and $\sigma_{\mathfrak{p}_1}+\sigma_{\mathfrak{p}_2}\ge\sigma_{19}+1$, we get $k-|R|\ge 33$, a contradiction.

(ii) Let d be even. Then from Lemma 7.6 $(ii),(iii),(iv)$, we get $\omega(d)=6,k<252$ and $\omega(d)=7,k<430$ if $2||d$; $\omega(d)=6,k<127$ and $\omega(d)=7,k<303$ if $4||d$; $\omega(d)=6,k<220$ if $8|d$. By Lemma 7.5, we obtain $\omega(d)=6$, $k<252$ and $\mathfrak{p}_1\ge 53$. Further by Lemma 7.6, we get $k-|R|\ge 2^{\omega(d)-\theta-1}+1$. This with Corollary

3.11 gives $\max(d_1, d_2) < (k-1)^2$ for some partition (d_1, d_2) of d. Since $\max(d_1, d_2) \geq \mathfrak{p}_1\mathfrak{p}_2\mathfrak{p}_3 \geq 53^3 > 430^2$, we get a contradiction. $\square$

Lemma 8.9. *Equation* (1.1) *with* $k \geq 101$ *implies that* $d > 10^{10}$.

Proof. Assume (1.1) with $k \geq 101$ and $d \leq 10^{10}$. By Lemma 8.2, we have $\omega(d) \geq 5$. Further we obtain from Corollary 8.5 that $k - |R| < 2^{\omega(d)-\theta}$ which we use without reference in the proof.

Let d be odd. Then $\omega(d) \leq 9$ otherwise $d \geq \prod_{i=2}^{11} p_i > 10^{10}$. By Lemma 8.8 (i), we see that $d > k^5 > 10^{10}$ if $\omega(d) = 5$. Thus $\omega(d) \geq 6$.

Let $\omega(d) = 6$. If $\mathfrak{p}_1 \leq 19$, then $d > k^5 > 10^{10}$ by Lemma 8.8 (i). Therefore $\mathfrak{p}_1 \geq 23$. Also $\mathfrak{p}_1 \leq 37$ otherwise $d \geq 41 \cdot 43 \cdot 47 \cdot 53 \cdot 59 \cdot 61 > 10^{10}$. Further $k < 556$ by Corollary 8.7. Therefore by Lemma 7.5 (b), we obtain $d \geq \min(23 \cdot 47 \cdot 53 \cdot 59 \cdot 61 \cdot 67, 31 \cdot 41 \cdot 47 \cdot 53 \cdot 59 \cdot 61) > 10^{10}$.

Thus $\omega(d) \geq 7$. Then $\mathfrak{p}_1 \leq 13$ otherwise $d \geq \prod_{j=7}^{13} p_i > 10^{10}$. Further $k \geq 1733$ otherwise $d \geq 3 \cdot 53^6 > 10^{10}$ by Lemma 7.5 (a). By Corollary 8.7, we obtain $\omega(d) \geq 8$.

Let $\omega(d) = 8$. Then $\mathfrak{p}_1 \leq 7$. Now Lemma 7.6 $(v), (vi)$ gives $\mathfrak{p}_1 \in \{5, 7\}$. Further $\mathfrak{p}_2 \leq 11$ since $5\prod_{j=6}^{12} p_i > 10^{10}$. This is not possible by Lemma 7.6 (vii) since $k \geq 1733$.

Let $\omega(d) = 9$. Then $\mathfrak{p}_1 = 3, \mathfrak{p}_2 = 5$ and $\mathfrak{p}_3 = 7$. This is not possible by Lemma 7.6 (vii) since $k \geq 1733$.

Let d be even. Then $\omega(d) \leq 10$ otherwise $d \geq \prod_{i=1}^{11} p_i > 10^{10}$. Further $\omega(d) \leq 9$ for $4|d$ since $4\prod_{i=2}^{10} p_i > 10^{10}$. By Lemma 8.8 (ii), we have $\omega(d) \geq 7$. Further $k \geq 1801$ by Lemma 7.5 (c) since $2\prod_{i=16}^{21} p_i > 10^{10}$. Now we use Lemma 7.6 $(ii), (iii), (iv)$ to obtain either $2||d, \omega(d) = 9, 10$ or $8|d, \omega(d) = 9$.

Let $2||d$. Let $\omega(d) = 9$. Then $\mathfrak{p}_1 \leq 5$ otherwise $d \geq 2\prod_{i=4}^{11} p_i > 10^{10}$. Then $k - |R| \geq 256$ by Lemma 7.6 (vii), a contradiction. Let $\omega(d) = 10$. Then $\mathfrak{p}_1 = 3, \mathfrak{p}_2 = 5$ and hence $k - |R| \geq 512$ by Lemma 7.6 (vii). This is not possible.

Let $8|d$ and $\omega(d) = 9$. Then $\mathfrak{p}_1 \leq 5$ since $8\prod_{i=4}^{11} p_i > 10^{10}$. By Lemma 7.6, we get $k - |R| \geq 512$ which is a contradiction. $\square$

9. Proof of Theorem 2

Suppose that (1.1) with $b = 1$ has a solution. By Theorem $\mathcal{A}$ (b), Lemmas 8.2, 8.6 and Corollary 8.7, we get $\omega(d) = 5, d$ odd, $k - |R| \leq 16$ and $110 \leq k < 308$. We observe that $\mathrm{ord}_p(a_0 a_1 \cdots a_{k-1})$ is even for each prime p. Therefore the number of i's for which a_i are divisible by p is at most $\sigma'_p = \lceil \frac{k}{p} \rceil$ or $\lceil \frac{k}{p} \rceil - 1$ according as $\lceil \frac{k}{p} \rceil$ is even or odd, respectively. Let $r = 4$. Then from (6.3), we get $k - |R| \geq k - F(k, r) - 2^r \geq k - \sum_{p > p_r} \sigma'_p - 2^r$ which is ≥ 17 except at $k = 110, 112, 114, 116, 118, 120, 122, 124$ where $k - |R| \geq 16$. Therefore $k = 110, 112, 114, 116, 118, 120, 122, 124$ and $k - |R| = 16$. Further we may assume that for each prime $11 \leq p \leq k$, there are exactly σ'_p number of i's for which $p|a_i$ and for any i, $pq \nmid a_i$ whenever $11 \leq q \leq k, q \neq p$. By considering the i's for which a_i's are divisible by primes $109, 107$ when $k = 110$; $37, 109, 107$ when $k = 112$; $113, 37, 109, 107$ when $k = 114$; $23, 113, 37, 109, 107$ when $k = 116$; $13, 23, 113, 37, 109, 107$ when $k = 118$; $17, 13, 23, 113, 37, 109, 107$ when $k = 120$; $11, 17, 13, 23, 113, 37, 109, 107$ when $k = 122$ and $41, 11, 17, 13, 23, 113, 37, 109, 107$ when $k = 124$, we get $P(a_{\varsigma_k} a_{\varsigma_k+1} \cdots a_{\varsigma_k+105}) \leq 103$ where $\varsigma_k = 2 + \frac{k-110}{2}$. This is excluded. For instance let $k = 124$. Then $P(a_9 a_{10} \cdots a_{114}) \leq 103$. This gives $103^2|a_j a_{j+103}$ for $j \in \{9, 10, 11\}$. Let $103^2|a_9 a_{112}$. Then $101^2|a_j a_{j+101}$ for $j \in \{10, 12, 13\}$ so that

$P(a_{14}a_{15}\cdots a_{110})\le 97$. This is excluded by considering by Theorem $\mathcal{A}$ with $k=97$. If $103^2|a_1a_{114}$, we obtain similarly that $P(a_{13}a_{14}\cdots a_{109})\le 97$ and it is excluded. Thus $103^2|a_{10}a_{113}$. If $101^2|a_ja_{j+101}$ for $j\in\{11,13\}$, we get $P(a_{14}a_{15}\cdots a_{110})\le 97$ and is excluded. Hence $101^2|a_9a_{110}$ implying $P(a_{11}a_{12}\cdots a_{107})\le 97$ and it is excluded again. □

10. Proof of Theorem 3

By Theorem $\mathcal{A}$ (a) and Lemmas 8.2, 8.8 (ii), we may suppose that d is odd, either $\omega(d)=3,(a_0,a_1,\cdots,a_{k-1})\in\mathfrak{S}_2$ or $\omega(d)\le 2,(a_0,a_1,\cdots,a_{k-1})\in\mathfrak{S}_1\cup\mathfrak{S}_2$, $(a_0,a_1,\cdots,a_7)\ne(3,1,5,6,7,2,1,10)$ or its mirror image when $k=8,\omega(d)=2$. For $p|d$, we observe from $\left(\frac{q}{p}\right)=1$ for $q\in\{2,3,5,7\}$ that $p\ge 311$ and therefore $d\ge 311^{\omega(d)}$. Further we observe from Lemma 4.2 that (3.24) is valid.

Let $\omega(d)=1$. If $k-|R|\ge 2$, we get $d=d_2<4(k-1)$ by Corollary 3.10 with $z_0=2$, a contradiction since $d\ge 311$. Therefore it remains to consider $k=8$ and $(a_0,\cdots,a_7)=(3,1,5,6,7,2,1,10)$ or its mirror image. We exclude the possibility $(a_0,\cdots,a_7)=(3,1,5,6,7,2,1,10)$ and the proof for excluding its mirror image is similar. We write

$$n=3x_0^2,\ n+d=x_1^2,\ n+2d=5x_2^2,\ n+3d=6x_3^2,$$
$$n+4d=7x_4^2,\ n+5d=2x_5^2,\ n+6d=x_6^2,\ n+7d=10x_7^2.$$

Then we get $5d=x_6^2-x_1^2=(x_6-x_1)(x_6+x_1)$ implying either $x_6-x_1=1,x_6+x_1=5d$ or $x_6-x_1=5,x_6+x_1=d$. We apply Runge's method to arrive at a contradiction. Suppose $x_6-x_1=1,x_6+x_1=5d$. Then $5d=2x_1+1$ and $x_1\ge 14$. We obtain $(125\cdot 6x_0x_3x_5)^2=(25(n+d)-25d)(25(n+d)+50d)(25(n+d)+100d)=(25x_1^2-10x_1-5)(25x_1^2+20x_1+10)(25x_1^2+40x_1+20)=15625x_1^6+31250x_1^5+20625x_1^4-3000x_1^3-10750x_1^2-6000x_1-1000=:\psi(x_1)$. We see that

$$(125x_1^3+125x_1^2+20x_1-32)^2>\psi(x_1)>(125x_1^3+125x_1^2+20x_1-33)^2.$$

This is a contradiction. Let $x_6-x_1=5,x_6+x_1=d$. Then we argue as above to conclude that $d=2x_1+5,x_1\ge 66$ and

$$(x_1^3+5x_1^2+4x_1-32)^2>\psi_1(x_1)>(x_1^3+5x_1^2+4x_1-33)^2$$

where $\psi_1(x_1)=x_1^6+10x_1^5+33x_1^4-24x_1^3-430x_1^2-1200x_1-1000$ is a square. This is again not possible.

Thus $\omega(d)\ge 2$. Let $k\ge 13$ and $(a_0,a_1,\cdots,a_{12})\ne(3,1,5,6,7,2,1,10,11,$
$3,13,14,15)$ or its mirror image when $k=13$. Let $\mathfrak{g}=3,4,5$ if $k=13,14,\ge 19$, respectively. Then from $\nu(1)=3$ and Lemma 3.9, we get a set Ω of pairs (i,j) with $|\Omega|\ge k-|R|+r_3\ge\mathfrak{g}$ having *Property ND*. Therefore there exists a non-degenerate double pair for $k\ge 14$ when $\omega(d)=2$. Further there are distinct pairs corresponding to partitions $(d_1,d_2),(d_2,d_1)$ for some divisor d_1 of d for $k\ge 13$ when $\omega(d)=2$ and for $k\ge 19$ when $\omega(d)=3$.

Suppose that there is a non-degenerate double pair. Then we get from Lemma 3.4 with $z_0=2$ that $d<3k^2\le 3\cdot 24^2$ contradicting $d\ge 311^2$. Thus there is no non-degenerate double pair corresponding to any partition. Again, if there are pairs $(i,j),(g,h)$ corresponding to partitions $(d_1,d_2),(d_2,d_1)$ for some divisor d_1 of d, then we derive from Lemma 3.3 that $d<(k-1)^4$. This is not possible since $311^2\le d<12^4$ when $\omega(d)=2$ and $311^3\le d<23^4$ when $\omega(d)=3$. Therefore there are no distinct pairs corresponding to partitions $(d_1, d_2), (d_2, d_1)$ for any divisor d_1 of d. Thus it remains to consider $k = 14$ when $\omega(d) = 3$ and either $k = 8, 9$ or $k = 13, (a_0, a_1, \cdots, a_{12}) = (3, 1, 5, 6, 7, 2, 1, 10, 11, 3, 13, 14, 15)$ or its mirror image when $\omega(d) = 2$. Also we may suppose that there is a pair (i, j) with $a_i = a_j$ corresponding to the partition $(1, d)$ for each of these possibilities.

Let $k = 8$ and $\omega(d) = 2$. We exclude the possibility $(a_0, a_1, \cdots, a_7) = (2, 3, 1, 5, 6, 7, 2, 1)$ and the proof for excluding its mirror image is similar. We see that either the pair $(0, 6)$ or $(2, 7)$ corresponds to $(1, d)$ and we arrive at a contradiction as in the case $k = 8, \omega(d) = 1$ and $(a_0, \cdots, a_7) = (3, 1, 5, 6, 7, 2, 1, 10)$. Let the pair $(0, 6)$ corresponds to $(1, d)$. Then either $x_6 - x_0 = 1, x_6 + x_0 = 3d$ or $x_6 - x_0 = 3, x_6 + x_0 = d$. Suppose $x_6 - x_0 = 1, x_6 + x_0 = 3d$. Then we obtain $3d = 2x_0 + 1, x_0 \geq 100$ and $(3x_2x_7)^2 = (3n + 6d)(3n + 21d) = (6x_0^2 + 4x_0 + 2)(6x_0^2 + 14x_0 + 7) = 36x_0^4 + 108x_0^3 + 110x_0^2 + 56x_0 + 14 := \psi_2(x_0)$ is a square. This is a contradiction since $(6x_0^2 + 9x_0 + 3)^2 > \psi_2(x_0) > (6x_0^2 + 9x_0 + 2)^2$. Let $x_6 - x_0 = 3, x_6 + x_0 = d$. Then we argue as above to conclude that $d = 2x_0 + 3, x_0 \geq 100$ and $4x_0^4 + 36x_0^3 + 11x_0^2 + 168x_0 + 126 := \psi_3(x_0)$ is a square. This is again not possible since $(2x_0^2 + 9x_0 + 8)^2 > \psi_3(x_0) > (2x_0^2 + 9x_0 + 7)^2$. The other possibility of the pair $(2, 7)$ corresponding to $(1, d)$ is excluded similarly.

Let $k = 9$ and $\omega(d) = 2$. Then (1.1) holds with $k = 8$ and $(a_0, \cdots, a_7) = (2, 3, 1, 5, 6, 7, 2, 1)$ or its mirror image. This is already excluded. The case $k = 13, \omega(d) = 2$ and $(a_0, \cdots, a_{12}) = (3, 1, 5, 6, 7, 2, 1, 10, 11, 3, 13, 14, 15)$ or its mirror image is excluded as above in the case $k = 8$.

Let $k = 14$ and $\omega(d) = 3$. Let $(a_0, \cdots, a_{13}) = (3, 1, 5, 6, 7, 2, 1, 10, 11, 3, 13, 14, 15, 1)$. Then one of the pairs $(0, 9), (1, 6), (1, 13), (6, 13)$ corresponds to the partition $(1, d)$. This is excluded as above in the case $k = 8, \omega(d) = 2$. The proof for excluding the mirror image $(1, 15, 14, 13, 3, 11, 10, 1, 2, 7, 6, 5, 1, 3)$ is similar. $\square$

11. Proof of Theorem 1

First we show that $d > 10^{10}$. By Lemma 8.9 and Theorem $\mathcal{A}$ (a), it suffices to consider the case $k = 7$ and $(a_0, a_1, \cdots, a_6)$ given by

$$(2, 3, 1, 5, 6, 7, 2),\ (3, 1, 5, 6, 7, 2, 1),\ (1, 5, 6, 7, 2, 1, 10) \tag{11.1}$$

or their mirror images. Then for $p|d$, we have $\left(\frac{q}{p}\right) = 1$ for $q \in \{2, 3, 5, 7\}$. Suppose that $d \leq 10^{10}$. Since $\omega(d) \geq 2$, we have $\mathfrak{p}_1 \leq 10^5$. For $X > 0$, let

$$\mathcal{P}_0 = \mathcal{P}_0(X) = \{p \leq X : \left(\frac{q}{p}\right) = 1,\ q = 2, 3, 5, 7\}.$$

We find that that $\mathcal{P}_0(10^5) = \{311, 479, 719, 839, 1009, \cdots\}$. Thus $\mathfrak{p}_1 \geq 311$ by $\mathfrak{p}_1 \in \mathcal{P}_0(10^5)$. Since $311 \cdot 479 \cdot 719 \cdot 839 > 10^{10}$, we have $\omega(d) \leq 3$. Further from $311^2 \cdot 479^2 > 10^{10}$, we get either $\omega(d) = 2, d = \mathfrak{p}_1\mathfrak{p}_2, \mathfrak{p}_1^2\mathfrak{p}_2, \mathfrak{p}_1\mathfrak{p}_2^2$ or $\omega(d) = 3, d = \mathfrak{p}_1\mathfrak{p}_2\mathfrak{p}_3$.

Consider $(a_0, a_1, \cdots, a_6) = (2, 3, 1, 5, 6, 7, 2)$. From $d = n + d - n = 3x_1^2 - 2x_0^2$, $3 \nmid x_0$, $4 \nmid x_0x_1$, we get $d \equiv -2 \equiv 1 (\text{mod } 3)$ and $d \equiv 3 - 2 \equiv 1 (\text{mod } 8)$ giving $d \equiv 1 (\text{mod } 24)$. Again from $2(x_6^2 - x_0^2) = n + 6d - n =$

$6d=6d_1d_2$, we get $x_6-x_0=r_1d_1, x_6+x_0=r_2d_2$ with $r_1r_2=3$, $r_1d_1<r_2d_2$ and $(r_1d_1,r_2d_2)\in\mathfrak{D}_3$ with

$$\mathfrak{D}_3=\begin{cases}\{(1,3\mathfrak{q}_1\mathfrak{q}_2),(3,\mathfrak{q}_1\mathfrak{q}_2),(\mathfrak{q}_1,3\mathfrak{q}_2),(3\mathfrak{q}_1,\mathfrak{q}_2),(\mathfrak{q}_2,3\mathfrak{q}_1)\} & \text{if } \omega(d)=2\\ \{(1,3\mathfrak{p}_1\mathfrak{p}_2\mathfrak{p}_3),(3,\mathfrak{p}_1\mathfrak{p}_2\mathfrak{p}_3),(\mathfrak{p}_1,3\mathfrak{p}_2\mathfrak{p}_3),(3\mathfrak{p}_1,\mathfrak{p}_2\mathfrak{p}_3), & \\ \ (\mathfrak{p}_2,3\mathfrak{p}_1\mathfrak{p}_3),(3\mathfrak{p}_2,\mathfrak{p}_1\mathfrak{p}_3),(\mathfrak{p}_3,3\mathfrak{p}_1\mathfrak{p}_2),(3\mathfrak{p}_3,\mathfrak{p}_1\mathfrak{p}_2)\} & \text{if } \omega(d)=3.\end{cases}$$

Then $x_0=\frac{r_2d_2-r_1d_1}{2}$ giving $x_2^2=n+2d=2x_0^2+2d_1d_2=\frac{1}{2}\{(r_1d_1)^2+(r_2d_2)^2-2d_1d_2\}$ a square. Now we see from $3x_1^2=n+d=2x_0^2+d=\frac{1}{2}\{(r_1d_1)^2+(r_2d_2)^2-4d_1d_2\}$ that $\frac{1}{6}\{(r_1d_1)^2+(r_2d_2)^2-4d_1d_2\}$ is an square. For each $d=\mathfrak{q}_1\mathfrak{q}_2$, we first check for $d\equiv 1(\text{mod } 24)$ and restrict to such d. Further for each possibility of $(r_1d_1,r_2d_2)\in\mathfrak{D}_3$ with $r_1d_1<r_2d_2$, we check for $\frac{1}{2}\{(r_1d_1)^2+(r_2d_2)^2-2d_1d_2\}$ being a square and restrict to such pairs (r_1d_1,r_2d_2). Finally we check that $\frac{1}{6}\{(r_1d_1)^2+(r_2d_2)^2-4d_1d_2\}$ is not a square. For example, let $d=1319\cdot 4919$. Then $\mathfrak{q}_1=1319,\mathfrak{q}_2=4919$. We check that $d\equiv 1(\text{mod } 24)$. For each choice $(r_1d_1,r_2d_2)\in\mathfrak{D}_3$ with $r_1d_1<r_2d_2$, we check for $\frac{1}{2}\{(r_1d_1)^2+(r_2d_2)^2-2d_1d_2\}$ being a square which is possible only for $(r_1d_1,r_2d_2)=(1319,3\cdot 4919)$. However we find that $\frac{1}{6}\{(r_1d_1)^2+(r_2d_2)^2-4d_1d_2\}$ is not a square for $(r_1d_1,r_2d_2)=(1319,3\cdot 4919)$.

Next we consider $(a_0,a_1,\cdots,a_6)=(3,1,5,6,7,2,1)$. From $d=n+6d-(n+5d)=x_6^2-2x_5^2$, $3\nmid x_5, 3|x_6^2$ and $2\nmid x_6, 4|x_5^2$, we get $d\equiv 1(\text{mod } 24)$. Again from $x_6^2-x_1^2=n+6d-(n+d)=5d=5d_1d_2$ we get $x_6-x_1=r_1d_1, x_6+x_1=r_2d_2$ with $r_1r_2=5$, $r_1d_1<r_2d_2$ and

$$\mathfrak{D}_5=\begin{cases}\{(1,5\mathfrak{q}_1\mathfrak{q}_2),(5,\mathfrak{q}_1\mathfrak{q}_2),(\mathfrak{q}_1,5\mathfrak{q}_2),(5\mathfrak{q}_1,\mathfrak{q}_2),(\mathfrak{q}_2,5\mathfrak{q}_1)\} & \text{if } \omega(d)=2\\ \{(1,5\mathfrak{p}_1\mathfrak{p}_2\mathfrak{p}_3),(5,\mathfrak{p}_1\mathfrak{p}_2\mathfrak{p}_3),(\mathfrak{p}_1,5\mathfrak{p}_2\mathfrak{p}_3),(5\mathfrak{p}_1,\mathfrak{p}_2\mathfrak{p}_3), & \\ \ (\mathfrak{p}_2,5\mathfrak{p}_1\mathfrak{p}_3),(5\mathfrak{p}_2,\mathfrak{p}_1\mathfrak{p}_3),(\mathfrak{p}_3,5\mathfrak{p}_1\mathfrak{p}_2),(5\mathfrak{p}_3,\mathfrak{p}_1\mathfrak{p}_2)\} & \text{if } \omega(d)=3.\end{cases}$$

Thus $x_6=\frac{r_2d_2+r_1d_1}{2}$ giving $2x_5^2=n+5d=x_6^2-d=\frac{1}{4}\{(r_1d_1)^2+(r_2d_2)^2+6d\}$ implying $\frac{1}{2}\{(r_1d_1)^2+(r_2d_2)^2+6d\}$ is a square. Further from $7x_4^2=n+4d=n+6d-2d=x_6^2-2d=\frac{1}{4}\{(r_1d_1)^2+(r_2d_2)^2+2d_1d_2\}$, we get $\frac{1}{7}\{(r_1d_1)^2+(r_2d_2)^2+2d_1d_2\}$ is a square. For each $d=\mathfrak{q}_1\mathfrak{q}_2$, we first check for $d\equiv 1(\text{mod } 24)$ and restrict to such d. Further for each possibility of $(r_1d_1,r_2d_2)\in\mathfrak{D}_5$ with $r_1d_1<r_2d_2$, we check for $\frac{1}{2}\{(r_1d_1)^2+(r_2d_2)^2+6d\}$ being a square and restrict to such pairs (r_1d_1,r_2d_2). Finally we check that $\frac{1}{7}\{(r_1d_1)^2+(r_2d_2)^2+2d\}$ is not a square. Further the case $(a_0,a_1,\cdots,a_6)=(1,5,6,7,2,1,10)$ is excluded by the preceding test.

The case $(a_0,a_1,\cdots,a_6)=(2,7,6,5,1,3,2)$ is similar to $(a_0,a_1,\cdots,a_6)=(2,3,1,5,6,7,2)$ and we obtain $d\equiv -1(\text{mod } 24)$, $\frac{1}{2}\{(r_1d_1)^2+(r_2d_2)^2+2d\}$ and $\frac{1}{6}\{(r_1d_1)^2+(r_2d_2)^2+4d\}$ are squares for each possibility of $(r_1d_1,r_2d_2)\in\mathfrak{D}_3$ with $r_1d_1<r_2d_2$. This is excluded. The cases $(a_0,a_1,\cdots,a_6)=(1,2,7,6,5,1,3),(10,1,2,7,6,5,1)$ are also similar to that of $(a_0,a_1,\cdots,a_6)=(3,1,5,6,7,2,1),(1,5,6,7,2,1,10)$ and is excluded. Thus $d>10^{10}$.

Now we show that $d>k^{\log\log k}$. Since $k^{\log\log k}<10^{10}$ for $k<22027$, we may assume that $k\ge 22027$. By Corollary 8.7, we obtain $\omega(d)\ge 9$ and $k<2(\omega(d)-\theta)2^{\omega(d)-\theta}=:\Psi_0(\omega(d)-\theta)$. Further we derive from $22027\le k<2\omega(d)2^{\omega(d)}$ that $\omega(d)\ge 11$. It suffices to show that $\log d>(\log\Psi_0(\omega(d)-\theta))(\log\log\Psi_0(\omega(d)-\theta))=:\Psi_1(\omega(d)-\theta)$. Let $\Psi_2(l)=l(\log l+\log\log l-1.076868)$ for $l>1$. From $d\ge 2^\delta\prod_{i=2}^{\omega(d)+1-\delta'}p_i$ and Lemma 5.1 (iv), we get $\log d>\Psi_2(\omega(d)+1)-\log 2, \Psi_2(\omega(d))+(\delta-1)\log 2$ when $2\nmid d, 2|d$, respectively. It suffices to check for $\omega(d)\ge 11$ that $\Psi_2(\omega(d)+1)-\log 2-\Psi_1(\omega(d))>0$ if $2\nmid d$, $\Psi_2(\omega(d))-\Psi_1(\omega(d)-1)>0$ if $2||d, 4||d$ and $\Psi_2(\omega(d))+\log 4-\Psi_1(\omega(d))>0$ if $8|d$. This is the case. $\square$

12. Theorem 2 with $\omega(d) = 2$ and $\gcd(n, d) \geq 1$

As stated in Section 1, we prove

Theorem 4. *A product of eight or more terms in arithmetic progression with common difference d satisfying $\omega(d) = 2$ is not a square.*

Proof. Suppose Theorem 4 is not true. Then (1.1) is valid with $k \geq 8, b = 1$ and $\omega(d) = 2$ but n and d not necessarily coprime. Let $n' = \frac{n}{\gcd(n,d)}$ and $d' = \frac{d}{\gcd(n,d)}$. Now, by dividing $\gcd(n, d)^k$ on both sides of (1.1), we have

$$n'(n' + d') \cdots (n' + (k-1)d') = \mathfrak{p}_1^{\delta_1}\mathfrak{p}_2^{\delta_2}y_1^2 \tag{12.1}$$

where $y_1 > 0$ is an integer and $\delta_1, \delta_2 \in \{0, 1\}$. We may assume that k is odd and $(\delta_1, \delta_2) \neq (0, 0)$ by Theorem 2 with $\omega(d) = 2$. Let $d' = 1$. Then we see from [SaSh03b, Corollary 3] that the left hand side of (12.1) is divisible by at least three primes $> k$. Therefore there exists a prime p with $p \neq \mathfrak{p}_1, p \neq \mathfrak{p}_2, p > k$ such that it divides a term on the left hand side of (12.1) to power at least 2. This implies $n' > k^2$. Now we see from [MuSh04b, Theorem 2] that the left hand side of (12.1) is divisible by at least three primes $> k$ to odd powers. This contradicts (12.1). Thus $d' > 1$ implying $(\delta_1, \delta_2) \neq (1, 1)$ by $\gcd(n', d') = 1$. Now we may assume that $(\delta_1, \delta_2) = (1, 0)$. Then d' is a power of $\mathfrak{p}_2$. Further we may suppose that $\mathfrak{p}_1 \geq k$ by the results stated in Section 1. Let $n + i_0 d$ with $0 \leq i_0 < k$ be the term divisible by $\mathfrak{p}_1$ on the left hand side of (12.1). Then

$$n' \cdots (n' + (i_0 - 1)d')(n' + (i_0 + 1)d') \cdots (n' + (k-1)d') = b'y_2^2$$

where $P(b') < k$ and $y_2 > 0$ is an integer. Now $k = 8$ by [MuSh04a, Theorem 1]. This is not possible since k is odd. $\square$

References

[BBGH06] M. Bennett, N. Bruin, K. Győry and L. Hajdu, *Powers from products of consecutive terms in arithmetic progression*, Proc. London Math. Soc. **92** (2006), 273-306.

[Dus98] P. Dusart, *Autour de la fonction qui compte le nombre de nombres premiers*, Ph.D thesis, Université de Limoges, 1998.

[Dus99] P. Dusart, *Inégalitiés explicites pour $\psi(X), \theta(X), \pi(X)$ et les nombres premiers*, C. R. Math. Rep. Acad. Sci. Canada **21(1)**(1999), 53-59, 55.

[ErSe75] P. Erdős and J.L. Selfridge, *The product of consecutive integers is never a power*, Illinois J. Math. **19** (1975), 292-301.

[FiHa01] P. Filakovszky and L. Hajdu, *The resolution of the Diophantine equation $x(x + d) \cdots (x + (k-1)d) = by^2$ for fixed d*, Acta Arith., **98** (2001), 151-154.

[HiLaShTi06] N. Hirata-Kohno, S. Laishram, T. N. Shorey and R. Tijdeman, *An extension of a theorem of Euler*, Acta Arith., to appear.

[Lai06] S. Laishram, *An estimate for the length of an arithmetic progression the product of whose terms is almost square*, Pub. Math. Debrecen, **68(3)** (2006), 451-475.

[LaSh06] S. Laishram and T. N. Shorey, *The greatest prime divisor of a product of terms in an arithmetic progression*, Indag. Math., **17(3)** (2006), 425-436.

[LaSh04] S. Laishram and T. N. Shorey, *Number of prime divisors in a product of terms of an arithmetic progression*, Indag. Math., **15(4)** (2004), 505-521.

[Mar85] R. Marszalek, *On the product of consecutive elements of an arithmetic progression,* Monatsh. für. Math. 100 (1985), 215-222.

[MuSh03] A. Mukhopadhyay and T. N. Shorey *Almost squares in arithmetic progression (II)*, Acta Arith., **110** (2003), 1-14.

[MuSh04a] A. Mukhopadhyay and T. N. Shorey *Almost squares in arithmetic progression (III)*, Indag. Math., **15** (2004), 523-533.

[MuSh04b] A. Mukhopadhyay and T. N. Shorey *Square free part of products of consecutive integers*, Publ. Math. Debrecen, **64** (2004), 79-99.

[Rob83] G. Robin,*Estimation de la fonction de Tchebychef θ sur le k-ième nombre premier et grandes valeurs de la fonction $\omega(n)$ nombre de diviseurs premiers de n*, Acta Arith., **42** (1983), 367-389.

[Rob55] H. Robbins, *A remark on stirling's formula*, Amer. Math. Monthly **62**, (1955). 26-29.

[RoSc62] J. B. Rosser and L. Schoenfeld, *Approximate formulas for some functions of prime numbers*, Illinois Jour. Math **6**(1962), 64-94.

[Sar97] N. Saradha, *On perfect powers in products with terms from arithmetic progressins*, Acta Arith., **82**, (1997), 147-172.

[SaSh03a] N. Saradha and T. N. Shorey, *Almost squares in arithmetic progression*, Compositio Math. **138** (2003), 73-111.

[SaSh03b] N. Saradha and T. N. Shorey, *Almost squares and factorisations in consecutive integers*, Compositio Math. **138** (2003), 113-124.

[SaSh05] N. Saradha and T. N. Shorey, *Contributions towards a conjecture of Erdos on perfect powers in arithmetic progressions*, Compositio Math., **141** (2005), 541-560.

[Sho02] T. N. Shorey, *Powers in arithmetic progression, A Panorama in Number Theory or The View from Baker's Garden*, edited by G.Wustholz, Cambridge University Press (2002), 341-353.

[ShTi90] T. N. Shorey and R. Tijdeman, *Perfect powers in products of terms in an arithmetical progression*, Compositio Math. **75** (1990), 307-344.

School of Mathematics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India
E-mail address: shanta@math.tifr.res.in
E-mail address: shorey@math.tifr.res.in