

On the counting function of sets with even partition functions

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*To Kálmán Győry, Attila Pethő, János Pintz and András Sárközy
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Abstract. Let q be an odd positive integer and $P \in \mathbb{F}_2[z]$ be of order q and such that $P(0) = 1$. We denote by $\mathcal{A} = \mathcal{A}(P)$ the unique set of positive integers satisfying $\sum_{n=0}^{\infty} p(\mathcal{A}, n)z^n \equiv P(z) \pmod{2}$, where $p(\mathcal{A}, n)$ is the number of partitions of n with parts in $\mathcal{A}$. In [5], it is proved that if $A(P, x)$ is the counting function of the set $\mathcal{A}(P)$ then $A(P, x) \ll x(\log x)^{-r/\varphi(q)}$, where r is the order of 2 modulo q and φ is the Euler's function. In this paper, we improve on the constant $c = c(q)$ for which $A(P, x) \ll x(\log x)^{-c}$.

1. Introduction

Let $\mathbb{N}$ be the set of positive integers and $\mathcal{A} = \{a_1, a_2, \dots\}$ be a subset of $\mathbb{N}$. For $n \in \mathbb{N}$, we denote by $p(\mathcal{A}, n)$ the number of partitions of n with parts in $\mathcal{A}$, i.e. the number of solutions of the equation

$$a_1x_1 + a_2x_2 + \dots = n,$$

in non-negative integers $x_1, x_2, \dots$. We set $p(\mathcal{A}, 0) = 1$.

Let $\mathbb{F}_2$ be the field with two elements and $f = 1 + \epsilon_1z + \dots + \epsilon_Nz^N + \dots \in \mathbb{F}_2[[z]]$. NICOLAS et al. proved (see [13], [4] and [11]) that there is a unique subset

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$\mathcal{A} = \mathcal{A}(f)$ of $\mathbb{N}$ such that

$$\sum_{n=0}^{\infty} p(\mathcal{A}, n) z^n \equiv f(z) \pmod{2}. \quad (1.1)$$

When f is a rational fraction, it has been shown in [11] that there is a polynomial U such that $\mathcal{A}(f)$ can be easily determined from $\mathcal{A}(U)$. When f is a general power series, nothing about the behaviour of $\mathcal{A}(f)$ is known. From now on, we shall restrict ourselves to the case $f = P$, where

$$P = 1 + \epsilon_1 z + \cdots + \epsilon_N z^N \in \mathbb{F}_2[z]$$

is a polynomial of degree $N \geq 1$.

Let $A(P, x)$ be the counting function of the set $\mathcal{A}(P)$, i.e.

$$A(P, x) = |\{n : 1 \leq n \leq x, n \in \mathcal{A}(P)\}|. \quad (1.2)$$

In [10], it is proved that

$$A(P, x) \geq \frac{\log x}{\log 2} - \frac{\log(N+1)}{\log 2}. \quad (1.3)$$

More attention was paid on upper bounds for $A(P, x)$. In [5, Theorem 3], it was observed that when P is a product of cyclotomic polynomials, the set $\mathcal{A}(P)$ is a union of geometric progressions of quotient 2 and so $A(P, x) = \mathcal{O}(\log x)$.

Let the decomposition of P into irreducible factors over $\mathbb{F}_2[z]$ be

$$P = P_1^{\alpha_1} P_2^{\alpha_2} \cdots P_l^{\alpha_l}.$$

We denote by β_i , $1 \leq i \leq l$, the order of $P_i(z)$, that is the smallest positive integer such that $P_i(z)$ divides $1 + z^{\beta_i}$ in $\mathbb{F}_2[z]$; it is known that β_i is odd (cf. [12]). We set

$$q = q(P) = \text{lcm}(\beta_1, \beta_2, \dots, \beta_l). \quad (1.4)$$

If $q = 1$ then $P(z) = 1 + z$ and $\mathcal{A}(P) = \{2^k, k \geq 0\}$, so that $A(P, x) = \mathcal{O}(\log x)$. We may suppose that $q \geq 3$. Now, let

$$\sigma(\mathcal{A}, n) = \sum_{d|n, d \in \mathcal{A}} d = \sum_{d|n} d \chi(\mathcal{A}, d), \quad (1.5)$$

where $\chi(\mathcal{A}, \cdot)$ is the characteristic function of the set $\mathcal{A}$,

$$\chi(\mathcal{A}, d) = \begin{cases} 1 & \text{if } d \in \mathcal{A} \\ 0 & \text{otherwise.} \end{cases}$$

In [6] (see also [3] and [2]), it is proved that for all $k \geq 0$, q is a period of the sequence $(\sigma(\mathcal{A}, 2^k n) \bmod 2^{k+1})_{n \geq 1}$, i.e.

$$n_1 \equiv n_2 \pmod{q} \Rightarrow \sigma(\mathcal{A}, 2^k n_1) \equiv \sigma(\mathcal{A}, 2^k n_2) \pmod{2^{k+1}} \quad (1.6)$$

and q is the smallest integer such that (1.6) holds for all k 's. Moreover, if n_1 and n_2 satisfy $n_2 \equiv 2^a n_1 \pmod{q}$ for some $a \geq 0$, then

$$\sigma(\mathcal{A}, 2^k n_2) \equiv \sigma(\mathcal{A}, 2^k n_1) \pmod{2^{k+1}}. \quad (1.7)$$

If m is odd and $k \geq 0$, let

$$S_{\mathcal{A}}(m, k) = \chi(\mathcal{A}, m) + 2\chi(\mathcal{A}, 2m) + \dots + 2^k \chi(\mathcal{A}, 2^k m). \quad (1.8)$$

It follows that for $n = 2^k m$, one has

$$\sigma(\mathcal{A}, n) = \sigma(\mathcal{A}, 2^k m) = \sum_{d|m} d S_{\mathcal{A}}(d, k), \quad (1.9)$$

which, by Möbius inversion formula, gives

$$m S_{\mathcal{A}}(m, k) = \sum_{d|m} \mu(d) \sigma\left(\mathcal{A}, \frac{n}{d}\right) = \sum_{d|\bar{m}} \mu(d) \sigma\left(\mathcal{A}, \frac{n}{d}\right), \quad (1.10)$$

where μ is the Möbius's function and $\bar{m} = \prod_{p|m} p$ is the radical of m , with $\bar{1} = 1$.

In [7] and [9], precise descriptions of the sets $\mathcal{A}(1+z+z^3)$ and $\mathcal{A}(1+z+z^3+z^4+z^5)$ are given and asymptotics to the related counting functions are obtained,

$$A(1+z+z^3, x) \sim c_1 \frac{x}{(\log x)^{\frac{3}{4}}}, \quad x \rightarrow \infty, \quad (1.11)$$

$$A(1+z+z^3+z^4+z^5, x) \sim c_2 \frac{x}{(\log x)^{\frac{1}{4}}}, \quad x \rightarrow \infty, \quad (1.12)$$

where $c_1 = 0.937\dots$, $c_2 = 1.496\dots$. In [1], the sets $\mathcal{A}(P)$ are considered when P is irreducible of prime order q and such that the order of 2 in $(\mathbb{Z}/q\mathbb{Z})^*$ is $\frac{q-1}{2}$. This situation is similar to that of $\mathcal{A}(1+z+z^3)$, and formula (1.11) can be extended to $A(P, x) \sim c' x (\log x)^{-3/4}$, $x \rightarrow \infty$, for some constant c' depending on P .

Let $P = QR$ be the product of two coprime polynomials in $\mathbb{F}_2[z]$. In [4], the following is given

$$A(P, x) \leq A(Q, x) + A(R, x) \quad (1.13)$$

and

$$|A(P, x) - A(R, x)| \leq \sum_{0 \leq i \leq \frac{\log x}{\log 2}} A\left(Q, \frac{x}{2^i}\right). \quad (1.14)$$

As an application of (1.14), choosing $Q = 1 + z + z^3$, $R = 1 + z + z^3 + z^4 + z^5$ and $P = QR$, we get from (1.11)–(1.14),

$$A(P, x) \sim A(R, x) \sim c_2 x (\log x)^{-1/4}, \quad x \rightarrow \infty.$$

In [5], a claim of NICOLAS and SÁRKÖZY [15], that some polynomials with $A(P, x) \asymp x$ may exist, was disapproved. More precisely, the following was obtained

Theorem 1.1. *Let $P \in \mathbb{F}_2[z]$ be such that $P(0) = 1$, $\mathcal{A} = \mathcal{A}(P)$ be the unique set obtained from (1.1) and q be the odd number defined by (1.4). Let r be the order of 2 modulo q , that is the smallest positive integer such that $2^r \equiv 1 \pmod{q}$. We shall say that a prime $p \neq 2$ is a bad prime if*

$$\exists i, \quad 0 \leq i \leq r-1 \text{ and } p \equiv 2^i \pmod{q}. \quad (1.15)$$

- (i) *If p is a bad prime, we have $\gcd(p, n) = 1$ for all $n \in \mathcal{A}$.*
- (ii) *There exists an absolute constant c_3 such that for all $x > 1$,*

$$A(P, x) \leq 7(c_3)^r \frac{x}{(\log x)^{\frac{r}{\varphi(q)}}}, \quad (1.16)$$

where φ is Euler's function.

2. The sets of bad and semi-bad primes

Let q be an odd integer ≥ 3 and r be the order of 2 modulo q . Let us call “bad classes” the elements of

$$\mathcal{E}(q) = \{1, 2, \dots, 2^{r-1}\} \subset (\mathbb{Z}/q\mathbb{Z})^*. \quad (2.1)$$

From (1.15), we know that an odd prime p is bad if $p \pmod{q}$ belongs to $\mathcal{E}(q)$. The set of bad primes will be denoted by $\mathcal{B}$. The fact that no element of $\mathcal{A}(P)$ is divisible by a bad prime (cf. Theorem 1.1 (i)) has given (cf. [5]) the upper bound (1.16). Two other sets of primes will be used to improve (1.16) cf. Theorem 2.1 below.

Remark 2.1. 2 is not a bad prime although it is a bad class.

Definition 2.1. A class of $(\mathbb{Z}/q\mathbb{Z})^*$ is said semi-bad if it does not belong to $\mathcal{E}(q)$ and its square does. A prime p is called semi-bad if its class modulo q is semi-bad. We denote by $\mathcal{E}'(q)$ the set of semi-bad classes, so that

$$p \text{ semi-bad} \iff p \pmod{q} \in \mathcal{E}'(q).$$

We denote by $|\mathcal{E}'(q)|$ the number of elements of $\mathcal{E}'(q)$.

Lemma 2.1. *Let q be an odd integer ≥ 3 , r be the order of 2 modulo q and*

$$q_2 = \begin{cases} 1 & \text{if 2 is a square modulo } q \\ 0 & \text{if not.} \end{cases}$$

The number $|\mathcal{E}'(q)|$ of semi-bad classes modulo q is given by

$$\begin{aligned} |\mathcal{E}'(q)| &= 2^{\omega(q)} \left(\left\lfloor \frac{r+1}{2} \right\rfloor + q_2 \left\lfloor \frac{r}{2} \right\rfloor \right) - r \\ &= \begin{cases} r(2^{\omega(q)-1} - 1) & \text{if } r \text{ is even and } q_2 = 0 \\ r(2^{\omega(q)} - 1) & \text{otherwise,} \end{cases} \end{aligned} \quad (2.2)$$

where $\omega(q)$ is the number of distinct prime factors of q and $\lfloor x \rfloor$ is the floor of x .

PROOF. We have to count the number of solutions of the r congruences

$$E_i : x^2 \equiv 2^i \pmod{q}, \quad 0 \leq i \leq r-1,$$

which do not belong to $\mathcal{E}(q)$. The number of solutions of E_0 is $2^{\omega(q)}$. The contribution of E_i when i is even is equal to that of E_0 by the change of variables $x = 2^{i/2}\xi$, so that the total number of solutions, in $(\mathbb{Z}/q\mathbb{Z})^*$, of the E'_i s for i even is equal to $\lfloor \frac{r+1}{2} \rfloor 2^{\omega(q)}$.

The number of odd i 's, $0 \leq i \leq r-1$, is equal to $\lfloor \frac{r}{2} \rfloor$. The contribution of all the E'_i s for these i 's are equal and vanish if $q_2 = 0$. When $q_2 = 1$, E_1 has $2^{\omega(q)}$ solutions in $(\mathbb{Z}/q\mathbb{Z})^*$. Hence the total number of solutions, in $(\mathbb{Z}/q\mathbb{Z})^*$, of the E'_i s for i odd is equal to $q_2 \lfloor \frac{r}{2} \rfloor 2^{\omega(q)}$.

Now, we have to remove those solutions which are in $\mathcal{E}(q)$. But any element 2^i , $0 \leq i \leq r-1$, from $\mathcal{E}(q)$ is a solution of the congruence $x^2 \equiv 2^j \pmod{q}$, where $j = 2i \pmod{r}$. Hence

$$|\mathcal{E}'(q)| = 2^{\omega(q)} \left(\left\lfloor \frac{r+1}{2} \right\rfloor + q_2 \left\lfloor \frac{r}{2} \right\rfloor \right) - r.$$

The second formula in (2.2) follows by noting that $q_2 = 1$ when r is odd. $\square$

Definition 2.2. A set of semi-bad classes is called a coherent set if it is not empty and if the product of any two of its elements is a bad class.

Lemma 2.2. *Let b be a semi-bad class; then*

$$\mathcal{C}_b = \{b, 2b, \dots, 2^{r-1}b\}$$

is a coherent set. There are no coherent sets with more than r elements.

PROOF. First, we observe that, for $0 \leq u \leq r-1$, $2^u b$ is semi-bad and, for $0 \leq u < v \leq r-1$, $(2^u b)(2^v b)$ is bad so that $\mathcal{C}_b$ is coherent.

Further, let $\mathcal{F}$ be a set of semi-bad classes with more than r elements; there exists in $\mathcal{F}$ two semi-bad classes a and b such that $a \notin \mathcal{C}_b$. Let us prove that ab is not bad. Indeed, if $ab \equiv 2^u \pmod{q}$ for some u , we would have $a \equiv 2^u b^{-1} \pmod{q}$. But, as b is semi-bad, b^2 is bad, i.e. $b^2 \equiv 2^v \pmod{q}$ for some v , which would imply $b \equiv 2^v b^{-1} \pmod{q}$, $b^{-1} \equiv b 2^{-v} \pmod{q}$, $a \equiv 2^{u-v} b \pmod{q}$ and $a \in \mathcal{C}_b$, a contradiction. Therefore, $\mathcal{F}$ is not coherent. $\square$

Lemma 2.3. *If $\omega(q) = 1$ and $\varphi(q)/r$ is odd, then $\mathcal{E}'(q) = \emptyset$; while if $\varphi(q)/r$ is even, the set of semi-bad classes $\mathcal{E}'(q)$ is a coherent set of r elements.*

If $\omega(q) \geq 2$, then $\mathcal{E}'(q) \neq \emptyset$ and there exists a coherent set $\mathcal{C}$ with $|\mathcal{C}| = r$.

PROOF. If $\omega(q) = 1$, q is a power of a prime number and the group $(\mathbb{Z}/q\mathbb{Z})^*$ is cyclic. Let g be some generator and d be the smallest positive integer such that $g^d \in \mathcal{E}(q)$, where $\mathcal{E}(q)$ is given by (2.1). We have $d = \varphi(q)/r$, since d is the order of the group $(\mathbb{Z}/q\mathbb{Z})^*/\mathcal{E}(q)$. The discrete logarithms of the bad classes are $0, d, 2d, \dots, (r-1)d$. The set $\mathcal{E}'(q) \cup \mathcal{E}(q)$ is equal to the union of the solutions of the congruences

$$x^2 \equiv g^{ad} \pmod{q} \quad (2.3)$$

for $0 \leq a \leq r-1$. By the change of variable $x = g^t$, (2.3) is equivalent to

$$2t \equiv ad \pmod{\varphi(q)}. \quad (2.4)$$

Let us assume first that d is odd so that r is even. If a is odd, the congruence (2.4) has no solution while, if a is even, say $a = 2b$, the solutions of (2.4) are $t \equiv bd \pmod{\varphi(q)/2}$ i.e.

$$t \equiv bd \pmod{\varphi(q)} \quad \text{or} \quad t \equiv bd + (r/2)d \pmod{\varphi(q)},$$

which implies

$$\mathcal{E}'(q) \cup \mathcal{E}(q) = \{g^0, g^d, \dots, g^{(r-1)d}\} = \mathcal{E}(q)$$

and $\mathcal{E}'(q) = \emptyset$.

Let us assume now that d is even. The congruence (2.4) is equivalent to

$$t \equiv ad/2 \pmod{\varphi(q)/2}$$

which implies $\mathcal{E}'(q) \cup \mathcal{E}(q) = \{g^{\alpha d/2}, 0 \leq \alpha \leq 2r-1\}$ yielding

$$\mathcal{E}'(q) = \{g^{\frac{d}{2}}, g^{3\frac{d}{2}}, \dots, g^{(2r-1)\frac{d}{2}}\} = \mathcal{C}_b$$

(with $b = (g^{\frac{d}{2}})$), which is coherent by Lemma 2.2.

If $\omega(q) \geq 2$, then, by Lemma 2.1, $\mathcal{E}'(q) \neq \emptyset$. Let $b \in \mathcal{E}'(q)$; by Lemma 2.2, the set $\mathcal{C}_b$ is a coherent set of r elements. $\square$

Let us set

$$c(q) = \begin{cases} \frac{3}{2} & \text{if } \mathcal{E}'(q) \neq \emptyset \\ 1 & \text{if } \mathcal{E}'(q) = \emptyset. \end{cases} \quad (2.5)$$

We shall prove

Theorem 2.1. *Let $P \in \mathbb{F}_2[z]$ with $P(0) = 1$, q be the odd integer defined by (1.4) and r be the order of 2 modulo q . We denote by $\mathcal{A}(P)$ the set obtained from (1.1) and by $A(P, x)$ its counting function. When x tends to infinity, we have*

$$A(P, x) \ll_q \frac{x}{(\log x)^{c(q) \frac{r}{\varphi(q)}}}, \quad (2.6)$$

where $c(q)$ is given by (2.5).

When P is irreducible, q is prime and $r = \frac{q-1}{2}$, the upper bound (2.6) is best possible; indeed in this case, from [1], we have $A(P, x) \asymp \frac{x}{(\log x)^{3/4}}$. As $\varphi(q)/r = 2$, Lemma 2.3 implies $\mathcal{E}'(q) \neq \emptyset$ so that $c = 3/2$ and in (2.6), the exponent of $\log x$ is $3/4$. Moreover, formula (1.12) gives the optimality of (2.6) for some prime ($q = 31$) satisfying $r = \frac{q-1}{6}$.

Theorem 2.2. *Let $P \in \mathbb{F}_2[z]$ be such that $P(0) = 1$ and $P = P_1 P_2 \cdots P_j$, where the P_i 's are irreducible polynomials in $\mathbb{F}_2[z]$. For $1 \leq i \leq j$, we denote by q_i the order of P_i , by r_i the order of 2 modulo q_i and we set $c = \min_{1 \leq i \leq j} c(q_i) r_i / \varphi(q_i)$, where $c(q_i)$ is given by (2.5). When x tends to infinity, we have*

$$A(P, x) \ll \frac{x}{(\log x)^c}. \quad (2.7)$$

where the symbol $\ll$ depends on the q_i 's, $1 \leq i \leq j$.

Let $\mathcal{C}$ be a coherent set of semi-bad classes modulo q . Let us associate to $\mathcal{C}$ the set of primes $\mathcal{S}$ defined by

$$p \in \mathcal{S} \iff p \bmod q \in \mathcal{C}. \quad (2.8)$$

We define $\omega_{\mathcal{S}}$ as the additive arithmetic function

$$\omega_{\mathcal{S}}(n) = \sum_{p|n, p \in \mathcal{S}} 1. \quad (2.9)$$

Lemma 2.4. *Let m be an odd positive integer, not divisible by any bad prime. If $\omega_{\mathcal{S}}(m) = k + 2 \geq 2$ then $2^h m \notin \mathcal{A}(P)$ for all h , $0 \leq h \leq k$. In other words, if $2^h m \in \mathcal{A}(P)$, then $h \geq \omega_{\mathcal{S}}(m) - 1$ holds.*

PROOF. Let us write $\overline{m} = m'm''$, with $m' = \prod_{p|\overline{m}, p \in \mathcal{S}} p$ and $m'' = \prod_{p|\overline{m}, p \notin \mathcal{S}} p$. From (1.10), if $n = 2^k m$ then

$$mS_{\mathcal{A}}(m, k) = \sum_{d|\overline{m}} \mu(d) \sigma\left(\mathcal{A}, \frac{n}{d}\right) = \sum_{d'|m'} \sum_{d''|m''} \mu(d') \mu(d'') \sigma\left(\mathcal{A}, \frac{n}{d'd''}\right). \quad (2.10)$$

Let us write $d' = p_{i_1} \cdots p_{i_j}$ and take some $p_{\mathcal{S}}$ from $\mathcal{S}$. If j is even then $\mu(d') = 1$ and, from the definition of a coherent set, $d' \equiv 2^t \pmod{q}$ for some t (depending on d'), $0 \leq t \leq r-1$. Whereas, if j is odd then $\mu(d') = -1$ and $d' \equiv 2^{t'} p_{\mathcal{S}}^{-1} \pmod{q}$ for some t' (depending on d'), $0 \leq t' \leq r-1$. From (1.7), we obtain

$$\mu(d') \sigma\left(\mathcal{A}, \frac{n}{d'd''}\right) \equiv \sigma\left(\mathcal{A}, \frac{n}{d''}\right) \pmod{2^{k+1}} \quad \text{if } j \text{ is even,} \quad (2.11)$$

$$\mu(d') \sigma\left(\mathcal{A}, \frac{n}{d'd''}\right) \equiv -\sigma\left(\mathcal{A}, \frac{np_{\mathcal{S}}}{d''}\right) \pmod{2^{k+1}} \quad \text{if } j \text{ is odd.} \quad (2.12)$$

Since $\alpha = \omega_{\mathcal{S}}(\overline{m}) = k+2 > 0$, the number of d' with odd j is equal to that with even j and is given by

$$1 + \binom{\alpha}{2} + \binom{\alpha}{4} + \cdots = \binom{\alpha}{1} + \binom{\alpha}{3} + \cdots = 2^{\alpha-1}.$$

From (2.10), we obtain

$$mS_{\mathcal{A}}(m, k) \equiv 2^{\alpha-1} \sum_{d''|m''} \mu(d'') \left(\sigma\left(\mathcal{A}, \frac{n}{d''}\right) - \sigma\left(\mathcal{A}, \frac{np_{\mathcal{S}}}{d''}\right) \right) \pmod{2^{k+1}}, \quad (2.13)$$

which, as $\alpha = \omega_{\mathcal{S}}(m) = k+2$, gives $S_{\mathcal{A}}(m, k) \equiv 0 \pmod{2^{k+1}}$, so that from (1.8),

$$\chi(\mathcal{A}, m) = \chi(\mathcal{A}, 2m) = \cdots = \chi(\mathcal{A}, 2^k m) = 0. \quad (2.14)$$

□

Let us assume that $\mathcal{E}'(q) \neq \emptyset$ so that there exists a coherent set $\mathcal{C}$ with r semi-bad classes modulo q ; we associate to $\mathcal{C}$ the set of primes $\mathcal{S}$ defined by (2.8) and we denote by $\mathcal{Q} = \mathcal{Q}(q)$ and $\mathcal{N} = \mathcal{N}(q)$ the sets

$$\mathcal{Q} = \{p \text{ prime, } p \mid q\} \quad \text{and} \quad \mathcal{N} = \{p \text{ prime, } p \notin \mathcal{B} \cup \mathcal{S} \text{ and } \gcd(p, 2q) = 1\},$$

so that the whole set of primes is equal to $\mathcal{B} \cup \mathcal{S} \cup \mathcal{N} \cup \mathcal{Q} \cup \{2\}$. For $n \geq 1$, let us define the multiplicative arithmetic function

$$\delta(n) = \begin{cases} 1 & \text{if } p \mid n \Rightarrow p \notin \mathcal{B} \quad (\text{i.e. } p \in \mathcal{S} \cup \mathcal{N} \cup \mathcal{Q} \cup \{2\}) \\ 0 & \text{otherwise.} \end{cases}$$

and for $x > 1$,

$$V(x) = V_q(x) = \sum_{n \geq 1, n2^{\omega_{\mathcal{S}}(n)} \leq x} \delta(n). \quad (2.15)$$

Lemma 2.5. *Under the above notation, we have*

$$V(x) = V_q(x) = \mathcal{O}_q \left(\frac{x}{(\log x)^{c(q) \frac{r}{\varphi(q)}}} \right), \quad (2.16)$$

where $c(q)$ is given by (2.5).

PROOF. To prove (2.16), one should consider, for complex s with $\Re(s) > 1$, the series

$$F(s) = \sum_{n \geq 1} \frac{\delta(n)}{(n 2^{\omega_S(n)})^s}. \quad (2.17)$$

This Dirichet series has an Euler's product given by

$$F(s) = \prod_{p \in \mathcal{N} \cup \mathcal{Q} \cup \{2\}} \left(1 - \frac{1}{p^s} \right)^{-1} \prod_{p \in \mathcal{S}} \left(1 + \frac{1}{2^s(p^s - 1)} \right), \quad (2.18)$$

which can be written as

$$F(s) = H(s) \prod_{p \in \mathcal{N}} \left(1 - \frac{1}{p^s} \right)^{-1} \prod_{p \in \mathcal{S}} \left(1 - \frac{1}{p^s} \right)^{-\frac{1}{2^s}}, \quad (2.19)$$

where

$$H(s) = \prod_{p \in \mathcal{Q} \cup \{2\}} \left(1 - \frac{1}{p^s} \right)^{-1} \prod_{p \in \mathcal{S}} \left(1 + \frac{1}{2^s(p^s - 1)} \right) \left(1 - \frac{1}{p^s} \right)^{\frac{1}{2^s}}. \quad (2.20)$$

By applying Selberg–Delange's formula (cf. [8], Théorème 1 and [9], Lemma 4.5), we obtain some constant c_4 such that

$$V(x) = c_4 \frac{x}{(\log x)^{c(q) \frac{r}{\varphi(q)}}} + \mathcal{O}_q \left(\frac{x \log \log x}{\log x} \right). \quad (2.21)$$

The constant c_4 is somewhat complicated, it is given by

$$c_4 = \frac{CH(1)}{\Gamma(1 - c(q) \frac{r}{\varphi(q)}), \quad (2.22)$$

where Γ is the gamma function,

$$H(1) = \frac{2q}{\varphi(q)} \prod_{p \in \mathcal{S}} \left(1 + \frac{1}{2(p-1)} \right) \left(1 - \frac{1}{p} \right)^{\frac{1}{2}} \quad (2.23)$$

and

$$C = \prod_{p \in \mathcal{N}} \left(1 - \frac{1}{p} \right)^{-1} \prod_{p \in \mathcal{S}} \left(1 - \frac{1}{p} \right)^{-\frac{1}{2}} \prod_p \left(1 - \frac{1}{p} \right)^{1 - c(q) \frac{r}{\varphi(q)}},$$

where in the third product, p runs over all primes. $\square$

3. Proof of the results

PROOF OF THEOREM 2.1. If $r = \varphi(q)$ then 2 is a generator of $(\mathbb{Z}/q\mathbb{Z})^*$, all primes are bad but 2 and the prime factors of q ; hence by Theorem 2 of [5], $A(P, x) = \mathcal{O}((\log x)^\kappa)$ for some constant κ , so that we may remove the case $r = \varphi(q)$.

If $\mathcal{E}'(q) = \emptyset$, from (2.5), $c = 1$ holds and (2.6) follows from (1.16).

We now assume $\mathcal{E}'(q) \neq \emptyset$, so that, from Lemma 2.2, there exists a coherent set $\mathcal{C}$ satisfying $|\mathcal{C}| = r$. We define the set of primes $\mathcal{S}$ by (2.8). Let us write $V(x)$ defined in (2.15) as

$$V(x) = V'(x) + V''(x), \quad (3.1)$$

with

$$V'(x) = \sum_{n \geq 1, n2^{\omega_{\mathcal{S}}(n)} \leq x, \omega_{\mathcal{S}}(n)=0} \delta(n) \quad \text{and} \quad V''(x) = \sum_{n \geq 1, n2^{\omega_{\mathcal{S}}(n)} \leq x, \omega_{\mathcal{S}}(n) \geq 1} \delta(n).$$

Similarly, we write $A(P, x) = \sum_{a \in \mathcal{A}(P), a \leq x} 1 = A' + A''$, with

$$A' = \sum_{a \in \mathcal{A}(P), a \leq x, \omega_{\mathcal{S}}(a)=0} 1 \quad \text{and} \quad A'' = \sum_{a \in \mathcal{A}(P), a \leq x, \omega_{\mathcal{S}}(a) \geq 1} 1.$$

An element a of $\mathcal{A}(P)$ counted in A' is free of bad and semi-bad primes, so that

$$A' \leq V'(x) \leq V'(2x). \quad (3.2)$$

By Lemma 2.4, an element a of $\mathcal{A}(P)$ counted in A'' is of the form $n2^{\omega_{\mathcal{S}}(n)-1}$ with $\omega_{\mathcal{S}}(n) = \omega_{\mathcal{S}}(a) \geq 1$; hence

$$A'' \leq V''(2x). \quad (3.3)$$

Therefore, from (3.1)–(3.3), we get

$$A(P, x) = A' + A'' \leq V'(2x) + V''(2x) = V(2x)$$

and (2.6) follows from Lemma 2.5. $\square$

PROOF OF THEOREM 2.2. Just use Theorem 2.1 and (1.13). $\square$

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