

On the parity of generalized partition functions, III

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RÉSUMÉ. Dans cet article, nous complétons les résultats de J.-L. Nicolas [15], en déterminant tous les éléments de l'ensemble $\mathcal{A} = \mathcal{A}(1 + z + z^3 + z^4 + z^5)$ pour lequel la fonction de partition $p(\mathcal{A}, n)$ (c-à-d le nombre de partitions de n en parts dans \mathcal{A}) est paire pour tout $n \geq 6$. Nous donnons aussi un équivalent asymptotique à la fonction de décompte de cet ensemble.

ABSTRACT. Improving on some results of J.-L. Nicolas [15], the elements of the set $\mathcal{A} = \mathcal{A}(1 + z + z^3 + z^4 + z^5)$, for which the partition function $p(\mathcal{A}, n)$ (i.e. the number of partitions of n with parts in \mathcal{A}) is even for all $n \geq 6$ are determined. An asymptotic estimate to the counting function of this set is also given.

1. Introduction.

Let \mathbb{N} (resp. \mathbb{N}_0) be the set of positive (resp. non-negative) integers. If $\mathcal{A} = \{a_1, a_2, \dots\}$ is a subset of \mathbb{N} and $n \in \mathbb{N}$ then $p(\mathcal{A}, n)$ is the number of partitions of n with parts in \mathcal{A} , i.e., the number of solutions of the diophantine equation

$$(1.1) \quad a_1x_1 + a_2x_2 + \dots = n,$$

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

The counting function of the set \mathcal{A} will be denoted by $A(x)$, i.e.,

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

Let \mathbb{F}_2 be the field with 2 elements, $P = 1 + \epsilon_1 z^1 + \dots + \epsilon_N z^N \in \mathbb{F}_2[z]$, $N \geq 1$. Although it is not difficult to prove (cf. [14], [5]) that there is a unique subset

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$\mathcal{A} = \mathcal{A}(P)$ of \mathbb{N} such that the generating function $F(z)$ satisfies

$$(1.3) \quad F(z) = F_{\mathcal{A}}(z) = \prod_{a \in \mathcal{A}} \frac{1}{1 - z^a} = \sum_{n \geq 0} p(\mathcal{A}, n) z^n \equiv P(z) \pmod{2},$$

the determination of the elements of such sets for general P 's seems to be hard.

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

$$(1.4) \quad P = P_1^{\alpha_1} P_2^{\alpha_2} \dots P_l^{\alpha_l}.$$

We denote by $\beta_i = \text{ord}(P_i)$, $1 \leq i \leq l$, the order of P_i , that is the smallest positive integer β_i such that $P_i(z)$ divides $1 + z^{\beta_i}$ in $\mathbb{F}_2[z]$. It is known that β_i is odd (cf. [13]). We set

$$(1.5) \quad \beta = \text{lcm}(\beta_1, \beta_2, \dots, \beta_l).$$

Let $\mathcal{A} = \mathcal{A}(P)$ satisfy (1.3) and $\sigma(\mathcal{A}, n)$ be the sum of the divisors of n belonging to \mathcal{A} , i.e.,

$$(1.6) \quad \sigma(\mathcal{A}, n) = \sum_{d|n, d \in \mathcal{A}} d = \sum_{d|n} d \chi(\mathcal{A}, d),$$

where $\chi(\mathcal{A}, \cdot)$ is the characteristic function of the set \mathcal{A} , i.e., $\chi(\mathcal{A}, d) = 1$ if $d \in \mathcal{A}$ and $\chi(\mathcal{A}, d) = 0$ if $d \notin \mathcal{A}$. It was proved in [6] (see also [4], [12]) that for all $k \geq 0$, the sequence $(\sigma(\mathcal{A}, 2^k n) \pmod{2^{k+1}})_{n \geq 1}$ is periodic with period β defined by (1.5), in other words,

$$(1.7) \quad n_1 \equiv n_2 \pmod{\beta} \Rightarrow \forall k \geq 0, \sigma(\mathcal{A}, 2^k n_1) \equiv \sigma(\mathcal{A}, 2^k n_2) \pmod{2^{k+1}}.$$

Moreover, the proof of (1.7) in [6] allows to calculate $\sigma(\mathcal{A}, 2^k n) \pmod{2^{k+1}}$ and to deduce the value of $\chi(\mathcal{A}, n)$ where n is any positive integer. Indeed, let

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

If n writes $n = 2^k m$ with $k \geq 0$ and m odd, (1.6) implies

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

which, by Möbius inversion formula, gives

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

where $\bar{m} = \prod_{p|m} p$ denotes the radical of m with $\bar{1} = 1$.

In the above sums, $\frac{n}{d}$ is always a multiple of 2^k , so that, from the values of $\sigma(\mathcal{A}, \frac{n}{d})$, by (1.10), one can determine the value of $S_{\mathcal{A}}(m, k) \pmod{2^{k+1}}$ and by (1.8), the value of $\chi(\mathcal{A}, 2^i m)$ for all $i, i \leq k$.

Let β be an odd integer ≥ 3 and $(\mathbb{Z}/\beta\mathbb{Z})^*$ be the group of invertible elements modulo β . We denote by $\langle 2 \rangle$ the subgroup of $(\mathbb{Z}/\beta\mathbb{Z})^*$ generated by 2 and consider its action \star on the set $\mathbb{Z}/\beta\mathbb{Z}$ given by $a \star x = ax$ for all $a \in \langle 2 \rangle$ and $x \in \mathbb{Z}/\beta\mathbb{Z}$. The quotient set will be denoted by $(\mathbb{Z}/\beta\mathbb{Z})/\langle 2 \rangle$ and the orbit of some n in $\mathbb{Z}/\beta\mathbb{Z}$ by $O(n)$. For $P \in \mathbb{F}_2[z]$ with $P(0) = 1$ and $\text{ord}(P) = \beta$, let $\mathcal{A} = \mathcal{A}(P)$ be the set obtained from (1.3). Property (1.7) shows (after [3]) that if n_1 and n_2 are in the same orbit then

$$(1.11) \quad \sigma(\mathcal{A}, 2^k n_1) \equiv \sigma(\mathcal{A}, 2^k n_2) \pmod{2^{k+1}}, \forall k \geq 0.$$

Consequently, for fixed k , the number of distinct values that $(\sigma(\mathcal{A}, 2^k n) \pmod{2^{k+1}})_{n \geq 1}$ can take is at most equal to the number of orbits of $\mathbb{Z}/\beta\mathbb{Z}$.

Let φ be the Euler function and s be the order of 2 modulo β , i.e., the smallest positive integer s such that $2^s \equiv 1 \pmod{\beta}$. If $\beta = p$ is a prime number then $(\mathbb{Z}/p\mathbb{Z})^*$ is cyclic and the number of orbits of $\mathbb{Z}/p\mathbb{Z}$ is equal to $1 + r$ with $r = \frac{\varphi(p)}{s} = \frac{p-1}{s}$. In this case, we have

$$(1.12) \quad (\mathbb{Z}/p\mathbb{Z})/\langle 2 \rangle = \{O(g), O(g^2), \dots, O(g^r) = O(1), O(p)\},$$

where g is some generator of $(\mathbb{Z}/p\mathbb{Z})^*$. For $r = 2$, the sets $\mathcal{A} = \mathcal{A}(P)$ were completely determined by N. Baccar, F. Ben Saïd and J.-L. Nicolas ([2], [8]). Moreover, N. Baccar proved in [1] that for all $r \geq 2$, the elements of \mathcal{A} of the form $2^k m$, $k \geq 0$ and m odd, are determined by the 2-adic development of some root of a polynomial with integer coefficients. Unfortunately, his results are not explicit and do not lead to any evaluation of the counting function of the set \mathcal{A} . When $r = 6$, J.-L. Nicolas determined (cf. [15]) the odd elements of $\mathcal{A} = \mathcal{A}(1 + z + z^3 + z^4 + z^5)$. His results (which will be stated in Section 2, Theorem 2.1) allowed to deduce a lower bound for the counting function of \mathcal{A} . In this paper, we will consider the case $p = 31$ which satisfies $r = 6$. In $\mathbb{F}_2[z]$, we have

$$(1.13) \quad \frac{1 - z^{31}}{1 - z} = P^{(1)} P^{(2)} \dots P^{(6)},$$

with

$$P^{(1)} = 1 + z + z^3 + z^4 + z^5, \quad P^{(2)} = 1 + z + z^2 + z^4 + z^5, \quad P^{(3)} = 1 + z^2 + z^3 + z^4 + z^5, \\ P^{(4)} = 1 + z + z^2 + z^3 + z^5, \quad P^{(5)} = 1 + z^2 + z^5, \quad P^{(6)} = 1 + z^3 + z^5.$$

In fact, there are other primes p with $r = 6$. For instance, $p = 223$ and $p = 433$.

In Section 2, for $\mathcal{A} = \mathcal{A}(P^{(1)})$, we evaluate the sum $S_{\mathcal{A}}(m, k)$ which will lead to results of Section 3 determining the elements of the set \mathcal{A} . Section 4 will be devoted to the determination of an asymptotic estimate to the counting function $A(x)$ of \mathcal{A} . Although, in this paper, the computations

are only carried out for $P = P^{(1)}$, the results could probably be extended to any $P^{(i)}$, $1 \leq i \leq 6$, and more generally, to any polynomial P of order p and such that $r = 6$.

Notation. We write $a \bmod b$ for the remainder of the euclidean division of a by b . The ceiling of the real number x is denoted by

$$\lceil x \rceil = \inf\{n \in \mathbb{Z}, x \leq n\}.$$

2. The sum $S_{\mathcal{A}}(m, k)$, $\mathcal{A} = \mathcal{A}(1 + z + z^3 + z^4 + z^5)$.

From now on, we take $\mathcal{A} = \mathcal{A}(P)$ with

$$(2.1) \quad P = P^{(1)} = 1 + z + z^3 + z^4 + z^5.$$

The order of P is $\beta = 31$. The smallest primitive root modulo 31 is 3 that we shall use as a generator of $(\mathbb{Z}/31\mathbb{Z})^*$. The order of 2 modulo 31 is $s = 5$ so that

$$(2.2) \quad (\mathbb{Z}/31\mathbb{Z})/\langle 2 \rangle = \{O(3), O(3^2), \dots, O(3^6) = O(1), O(31)\},$$

with

$$(2.3) \quad O(3^j) = \{2^k 3^j, 0 \leq k \leq 4\}, 1 \leq j \leq 6$$

and

$$(2.4) \quad O(31) = \{31\}.$$

For $k \geq 0$ and $0 \leq j \leq 5$, we define the integers $u_{k,j}$ by

$$(2.5) \quad u_{k,j} = \sigma(\mathcal{A}, 2^k 3^j) \bmod 2^{k+1}.$$

The Graeffe transformation. Let \mathbb{K} be a field and $\mathbb{K}[[z]]$ be the ring of formal power series with coefficients in \mathbb{K} . For an element

$$f(z) = a_0 + a_1 z + a_2 z^2 + \dots + a_n z^n + \dots$$

of this ring, the product

$$f(z)f(-z) = b_0 + b_1 z^2 + b_2 z^4 + \dots + b_n z^{2n} + \dots$$

is an even power series. We shall call $\mathcal{G}(f)$ the series

$$(2.6) \quad \mathcal{G}(f)(z) = b_0 + b_1 z + b_2 z^2 + \dots + b_n z^n + \dots$$

It follows immediately from the above definition that for $f, g \in \mathbb{K}[[z]]$,

$$(2.7) \quad \mathcal{G}(fg) = \mathcal{G}(f)\mathcal{G}(g).$$

Moreover if q is an odd integer and $f(z) = 1 - z^q$, we have $\mathcal{G}(f) = f$. We shall use the following notation for the iterates of f by \mathcal{G} :

$$(2.8) \quad f_{(0)} = f, f_{(1)} = \mathcal{G}(f), \dots, f_{(k)} = \mathcal{G}(f_{(k-1)}) = \mathcal{G}^{(k)}(f).$$

More details about the Graeffe transformation are given in [6]. By making the logarithmic derivative of formula (1.3), we get (cf. [14]):

$$(2.9) \quad \sum_{n=1}^{\infty} \sigma(\mathcal{A}, n) z^n = z \frac{F'(z)}{F(z)} \equiv z \frac{P'(z)}{P(z)} \pmod{2},$$

which, by Propositions 2 and 3 of [6], leads to

$$(2.10) \quad \sum_{n=1}^{\infty} \sigma(\mathcal{A}, 2^k n) z^n \equiv z \frac{P'_{(k)}(z)}{P_{(k)}(z)} = \frac{z}{1 - z^{31}} \left(P'_{(k)}(z) W_{(k)}(z) \right) \pmod{2^{k+1}},$$

with $P'_{(k)}(z) = \frac{d}{dz}(P_{(k)}(z))$ and

$$(2.11) \quad W(z) = (1 - z)P^{(2)}(z) \dots P^{(6)}(z).$$

Formula (2.10) proves (1.11) with $\beta = 31$, and the computation of the k -th iterates $P_{(k)}$ and $W_{(k)}$ by the Graeffe transformation yields the value of $\sigma(\mathcal{A}, 2^k n) \bmod 2^{k+1}$. For instance, for $k = 11$, we obtain:

$$u_{k,0} = 1183, u_{k,1} = 1598, u_{k,2} = 1554, u_{k,3} = 845, u_{k,4} = 264, u_{k,5} = 701.$$

A divisor of $2^k 3^j$ is either a divisor of $2^{k-1} 3^j$ or a multiple of 2^k . Therefore, from (2.5) and (1.6), $u_{k,j} \equiv u_{k-1,j} \pmod{2^k}$ holds and the sequence $(u_{k,j})_{k \geq 0}$ defines a 2-adic integer U_j satisfying for all k 's:

$$(2.12) \quad U_j \equiv u_{k,j} \pmod{2^{k+1}}, 0 \leq j \leq 5.$$

It has been proved in [1] that the U_j 's are the roots of the polynomial

$$R(y) = y^6 - y^5 + 3y^4 - 11y^3 + 44y^2 - 36y + 32.$$

Note that $R(y)^5$ is the resultant in z of $\phi_{31}(z) = 1 + z + \dots + z^{30}$ and $y + z + z^2 + z^4 + z^8 + z^{16}$.

Let us set

$$\theta = U_0 = 1 + 2 + 2^2 + 2^3 + 2^4 + 2^7 + 2^{10} + \dots$$

It turns out that the Galois group of $R(y)$ is cyclic of order 6 and therefore the other roots U_1, \dots, U_5 of $R(y)$ are polynomials in θ . With Maple, by factorizing $R(y)$ on $\mathbb{Q}[\theta]$ and using the values of $u_{11,j}$, we get

$$U_0 = \theta \equiv 1183 \pmod{2^{11}}$$

$$U_1 = \frac{1}{32}(3\theta^5 + 5\theta^3 - 36\theta^2 + 84\theta) \equiv 1598 \pmod{2^{11}}$$

$$U_2 = \frac{1}{32}(-3\theta^5 - 5\theta^3 + 20\theta^2 - 100\theta) \equiv 1554 \pmod{2^{11}}$$

$$U_3 = \frac{1}{32}(-\theta^5 - 7\theta^3 + 12\theta^2 - 44\theta + 32) \equiv 845 \pmod{2^{11}}$$

$$U_4 = \frac{1}{32}(-\theta^5 + 4\theta^4 + \theta^3 + 24\theta^2 - 68\theta + 96) \equiv 264 \pmod{2^{11}}$$

$$(2.13) \quad U_5 = \frac{1}{16}(\theta^5 - 2\theta^4 + 3\theta^3 - 10\theta^2 + 48\theta - 48) \equiv 701 \pmod{2^{11}}.$$

For convenience, if $j \in \mathbb{Z}$, we shall set

$$(2.14) \quad U_j = U_{j \bmod 6}.$$

We define the completely additive function $\ell : \mathbb{Z} \setminus 31\mathbb{Z} \rightarrow \mathbb{Z}/6\mathbb{Z}$ by

$$(2.15) \quad \ell(n) = j \quad \text{if } n \in O(3^j),$$

so that $\ell(n_1 n_2) \equiv \ell(n_1) + \ell(n_2) \pmod{6}$. We split the odd primes different from 31 into six classes according to the value of ℓ . More precisely, for $0 \leq j \leq 5$,

$$(2.16) \quad p \in \mathcal{P}_j \iff \ell(p) = j \iff p \equiv 2^k 3^j \pmod{31}, \quad k = 0, 1, 2, 3, 4.$$

We take $L : \mathbb{N} \setminus 31\mathbb{N} \rightarrow \mathbb{N}_0$ to be the completely additive function defined on primes by

$$(2.17) \quad L(p) = \ell(p).$$

We define, for $0 \leq j \leq 5$, the additive function $\omega_j : \mathbb{N} \rightarrow \mathbb{N}_0$ by

$$(2.18) \quad \omega_j(n) = \sum_{p|n, p \in \mathcal{P}_j} 1 = \sum_{p|n, \ell(p)=j} 1,$$

and $\omega(n) = \omega_0(n) + \dots + \omega_5(n) = \sum_{p|n} 1$. We remind that additive functions vanish on 1.

From (2.5), (2.3), (1.11) and (2.12), it follows that if $n = 2^k m \in O(3^j)$ (so that $j = \ell(n) = \ell(m)$),

$$(2.19) \quad \sigma(\mathcal{A}, n) = \sigma(\mathcal{A}, 2^k m) \equiv U_{\ell(m)} \pmod{2^{k+1}}.$$

We may consider the 2-adic number

$$(2.20) \quad S(m) = S_{\mathcal{A}}(m) = \chi(\mathcal{A}, m) + 2\chi(\mathcal{A}, 2m) + \dots + 2^k \chi(\mathcal{A}, 2^k m) + \dots$$

satisfying from (1.8),

$$(2.21) \quad S(m) \equiv S_{\mathcal{A}}(m, k) \pmod{2^{k+1}}.$$

Then (1.10) implies for $\gcd(m, 31) = 1$,

$$(2.22) \quad mS(m) = \sum_{d|\bar{m}} \mu(d) U_{\ell(\frac{m}{d})}.$$

If 31 divides m , it was proved in [3, (3.6)] that, for all k 's,

$$(2.23) \quad \sigma(\mathcal{A}, 2^k m) \equiv -5 \pmod{2^{k+1}}.$$

Remark 2.1. No element of \mathcal{A} has a prime factor in \mathcal{P}_0 . This general result has been proved in [3], but we recall the proof on our example: let us assume that $n = 2^k m \in \mathcal{A}$, where m is an odd integer divisible by some prime p in \mathcal{P}_0 , in other words $\omega_0(m) \geq 1$. (1.10) gives

$$\begin{aligned} mS_{\mathcal{A}}(m, k) &= \sum_{d|m} \mu(d) \sigma\left(\mathcal{A}, \frac{n}{d}\right) = \sum_{d|\bar{m}} \mu(d) \sigma\left(\mathcal{A}, 2^k \frac{m}{d}\right) \\ &= \sum_{d|\frac{\bar{m}}{p}} \mu(d) \sigma\left(\mathcal{A}, 2^k \frac{m}{d}\right) + \sum_{d|\frac{\bar{m}}{p}} \mu(pd) \sigma\left(\mathcal{A}, 2^k \frac{m}{pd}\right) \\ &= \sum_{d|\frac{\bar{m}}{p}} \mu(d) \left(\sigma\left(\mathcal{A}, 2^k \frac{m}{d}\right) - \sigma\left(\mathcal{A}, 2^k \frac{m}{pd}\right) \right). \end{aligned}$$

In the above sum, both $\frac{m}{d}$ and $\frac{m}{pd}$ are in the same orbit, so that from (1.11), $\sigma(\mathcal{A}, 2^k \frac{m}{d}) \equiv \sigma(\mathcal{A}, 2^k \frac{m}{pd}) \pmod{2^{k+1}}$ and therefore $mS_{\mathcal{A}}(m, k) \equiv 0 \pmod{2^{k+1}}$. Since m is odd and (cf. (1.8)) $0 \leq S_{\mathcal{A}}(m, k) < 2^{k+1}$ then $S_{\mathcal{A}}(m, k) = 0$, so that by (1.8), $2^k m \notin \mathcal{A}$, for all $0 \leq k \leq 5$.

In [15], J.-L. Nicolas has described the odd elements of \mathcal{A} . In fact, he obtained the following:

Theorem 2.1. ([15])

(a) The odd elements of \mathcal{A} which are primes or powers of primes are of the form p^λ , $\lambda \geq 1$, satisfying one of the following four conditions:

$$\begin{aligned} p \in \mathcal{P}_1 \quad \text{and} \quad \lambda &\equiv 1, 3, 4, 5 \pmod{6} \\ p \in \mathcal{P}_2 \quad \text{and} \quad \lambda &\equiv 0, 1 \pmod{3} \\ p \in \mathcal{P}_4 \quad \text{and} \quad \lambda &\equiv 0, 1 \pmod{3} \\ p \in \mathcal{P}_5 \quad \text{and} \quad \lambda &\equiv 0, 2, 3, 4 \pmod{6}. \end{aligned}$$

(b) No odd element of \mathcal{A} is a multiple of 31^2 . If m is odd, $m \neq 1$, and not a multiple of 31, then

$$m \in \mathcal{A} \quad \text{if and only if } 31m \in \mathcal{A}.$$

(c) An odd element $n \in \mathcal{A}$ satisfies $\omega_0(n) = 0$ and $\omega_3(n) = 0$ or 1; in other words, n is free of prime factor in \mathcal{P}_0 and has at most one prime factor in \mathcal{P}_3 .

(d) The odd elements of \mathcal{A} different from 1, not divisible by 31, which are not primes or powers of primes are exactly the odd n 's, $n \neq 1$, such that (where $\bar{n} = \prod_{p|n} p$):

- (1) $\omega_0(n) = 0$ and $\omega_3(n) = 0$ or 1.
- (2) If $\omega_3(n) = 1$ then $\ell(n) + \ell(\bar{n}) \equiv 0$ or 1 $\pmod{3}$.

(3) If $\omega_3(n) = 0$ and $\omega_1(n) + \ell(n) - \ell(\bar{n})$ is even then

$$2\ell(n) - \ell(\bar{n}) \equiv 2 \text{ or } 3 \text{ or } 4 \text{ or } 5 \pmod{6}.$$

(4) If $\omega_3(n) = 0$ and $\omega_1(n) + \ell(n) - \ell(\bar{n})$ is odd then

$$2\ell(n) - \ell(\bar{n}) \equiv 0 \text{ or } 4 \pmod{6}.$$

Remark 2.2. Point (b) of Theorem 2.1 can be improved in the following way: No element of \mathcal{A} is a multiple of 31^2 . Indeed, from (1.10), we have for m odd, $k \geq 0$ and $\tau \geq 2$,

$$\begin{aligned} 31^\tau m S_{\mathcal{A}}(31^\tau m, k) &= \sum_{d|31^\tau m} \mu(d) \sigma\left(\mathcal{A}, 2^k 31^\tau \frac{m}{d}\right) \\ &= \sum_{d|31\bar{m}} \mu(d) \sigma\left(\mathcal{A}, 2^k 31^\tau \frac{m}{d}\right) \\ &= \sum_{d|\bar{m}} \mu(d) \left\{ \sigma\left(\mathcal{A}, 2^k 31^\tau \frac{m}{d}\right) - \sigma\left(\mathcal{A}, 2^k 31^{\tau-1} \frac{m}{d}\right) \right\}. \end{aligned}$$

Since $31^\tau \frac{m}{d}$ and $31^{\tau-1} \frac{m}{d}$ are in the same orbit $O(31)$ then (1.11) and (2.23) give $\sigma(\mathcal{A}, 2^k 31^\tau \frac{m}{d}) \equiv \sigma(\mathcal{A}, 2^k 31^{\tau-1} \frac{m}{d}) \equiv -5 \pmod{2^{k+1}}$, so that we get $S_{\mathcal{A}}(31^\tau m, k) \equiv 0 \pmod{2^{k+1}}$. Hence, from (1.8), $S_{\mathcal{A}}(31^\tau m, k) = 0$ and for all $0 \leq h \leq k$ and all $\tau \geq 2$, $2^h 31^\tau m$ does not belong to \mathcal{A} .

In view of stating Theorem 2.2 which will extend Theorem 2.1, we shall need some notation. The radical \bar{m} of an odd integer $m \neq 1$, not divisible by 31 and free of prime factors belonging to \mathcal{P}_0 will be written

$$(2.24) \quad \bar{m} = p_1 \cdots p_{\omega_1} p_{\omega_1+1} \cdots p_{\omega_1+\omega_2} p_{\omega_1+\omega_2+1} \cdots p_{\omega_1+\omega_2+\omega_3+\omega_4+1} \cdots p_{\omega},$$

where $\ell(p_i) = j$ for $\omega_1 + \dots + \omega_{j-1} + 1 \leq i \leq \omega_1 + \dots + \omega_j$, $\omega_j = \omega_j(m) = \omega_j(\bar{m})$ and $\omega = \omega(m) = \omega(\bar{m}) \geq 1$. We define the additive functions from $\mathbb{Z} \setminus 31\mathbb{Z}$ into $\mathbb{Z}/12\mathbb{Z}$:

$$(2.25) \quad \alpha = \alpha(m) = 2\omega_5 - 2\omega_1 + \omega_4 - \omega_2 \pmod{12},$$

$$(2.26) \quad a = a(m) = \omega_5 - \omega_1 + \omega_2 - \omega_4 \pmod{12}.$$

Let $(v_i)_{i \in \mathbb{Z}}$ be the periodic sequence of period 12 defined by

$$(2.27) \quad v_i = \begin{cases} \frac{2}{\sqrt{3}} \cos(i\frac{\pi}{6}) & \text{if } i \text{ is odd} \\ 2 \cos(i\frac{\pi}{6}) & \text{if } i \text{ is even.} \end{cases}$$

The values of $(v_i)_{i \in \mathbb{Z}}$ are given by:

$i =$	0	1	2	3	4	5	6	7	8	9	10	11
$v_i =$	2	1	1	0	-1	-1	-2	-1	-1	0	1	1

Note that

$$(2.28) \quad v_{i+6} = -v_i,$$

$$(2.29) \quad v_i + v_{i+2} = \begin{cases} v_{i+1} & \text{if } i \text{ is odd} \\ 3v_{i+1} & \text{if } i \text{ is even,} \end{cases}$$

$$(2.30) \quad v_{2i} \equiv -2^i \pmod{3}$$

and

$$(2.31) \quad v_i \equiv v_{i+3} \equiv v_{2i} \pmod{2}.$$

From the U_j 's (cf. (2.12) and (2.13)), we introduce the following 2-adic integers:

$$(2.32) \quad E_i = \sum_{j=0}^5 v_{i+2j} U_j, \quad i \in \mathbb{Z},$$

$$(2.33) \quad F_i = \sum_{j=0}^5 v_{i+4j} U_j, \quad i \in \mathbb{Z},$$

$$(2.34) \quad G = \sum_{j=0}^5 (-1)^j U_j.$$

From (2.28), we have

$$(2.35) \quad E_{i+6} = -E_i, \quad E_{i+12} = E_i, \quad F_{i+6} = -F_i, \quad F_{i+12} = F_i.$$

From (2.29), it follows that, if i is odd,

$$(2.36) \quad E_i + E_{i+2} = E_{i+1}, \quad F_i + F_{i+2} = F_{i+1},$$

while, if i is even,

$$(2.37) \quad E_i + E_{i+2} = 3E_{i+1}, \quad F_i + F_{i+2} = 3F_{i+1},$$

The values of these numbers are given in the following array:

Z	$Z \bmod 2^4$
$E_0 = \frac{1}{32}(11\theta^5 - 8\theta^4 + 29\theta^3 - 124\theta^2 + 500\theta - 256)$	1157
$E_1 = \frac{1}{16}(3\theta^5 - 2\theta^4 + 9\theta^3 - 26\theta^2 + 136\theta - 64)$	1533
$E_2 = 3E_1 - E_0$	1394
$E_3 = 2E_1 - E_0$	1909
$E_4 = 3E_1 - 2E_0$	237
$E_5 = E_1 - E_0$	376
$F_0 = \frac{1}{32}(-3\theta^5 - 21\theta^3 + 36\theta^2 - 36\theta + 64)$	1987
$F_1 = \frac{1}{32}(-3\theta^5 - 4\theta^4 - 13\theta^3 + 24\theta^2 - 28\theta - 64)$	166
$F_2 = 3F_1 - F_0$	559
$F_3 = 2F_1 - F_0$	393
$F_4 = 3F_1 - 2F_0$	620
$F_5 = F_1 - F_0$	227
$G = \frac{1}{4}(-\theta^5 + \theta^4 - \theta^3 + 11\theta^2 - 34\theta + 20)$	1905

TABLE 1

Lemma 2.1. *The polynomials $(U_j)_{0 \leq j \leq 5}$ (cf. (2.13)) form a basis of $\mathbb{Q}[\theta]$. The polynomials $E_0, E_1, F_0, F_1, G, U_0$ form another basis of $\mathbb{Q}[\theta]$. For all i 's, E_i and F_i are linear combinations of respectively E_0 and E_1 and F_0 and F_1 .*

Proof. With Maple, in the basis $1, \theta, \dots, \theta^5$, we compute determinant $(U_0, \dots, U_5) = \frac{1}{1024}$. From (2.32), (2.33) and (2.34), the determinant of $(E_0, E_1, F_0, F_1, G, U_0)$ in the basis U_0, U_1, \dots, U_5 is equal to 12. The last point follows from (2.36) and (2.37). \square

We have

Theorem 2.2. *Let $m \neq 1$ be an odd integer not divisible by 31 with \bar{m} of the form (2.24). Under the above notation and the convention*

$$(2.38) \quad 0^\omega = \begin{cases} 1 & \text{if } \omega = 0 \\ 0 & \text{if } \omega > 0, \end{cases}$$

we have:

(1) *The 2-adic integer $S(m)$ defined by (2.20) satisfies*

$$(2.39) \quad mS(m) = 2^{\omega_3-1} 3^{\lceil \frac{\omega_2+\omega_4}{2} - 1 \rceil} E_{\alpha-2\ell(m)} + \frac{0^{\omega_3}}{2} 3^{\lceil \frac{\omega}{2} - 1 \rceil} F_{\alpha-4\ell(m)} + \frac{0^{\omega_2+\omega_4}}{3} 2^{\omega-1} (-1)^{\ell(m)} G.$$

(2) *The 2-adic integer $S(31m)$ satisfies*

$$(2.40) \quad S(31m) = -31^{-1} S(m),$$

where 31^{-1} is the inverse of 31 in \mathbb{Z}_2 . In particular, for all $k \in \{0, 1, 2, 3, 4\}$, we have

$$2^k m \in \mathcal{A} \iff 31 \cdot 2^k m \in \mathcal{A},$$

since the inverse of 31 modulo 2^{k+1} is -1 for $k \leq 4$.

Proof of Theorem 2.2 (1). From (2.22), we have

$$(2.41) \quad mS(m) = \sum_{d|\bar{m}} \mu(d) U_{\ell(\frac{m}{d})} = \sum_{d|\bar{m}} \mu(d) U_{\ell(m)-\ell(d)}.$$

Further, (2.41) becomes

$$(2.42) \quad mS(m) = \sum_{j=0}^5 T(m, j) U_{\ell(m)-j} = \sum_{j=0}^5 T(m, \ell(m) - j) U_j,$$

with

$$(2.43) \quad T(m, j) = T(\bar{m}, j) = \sum_{d|\bar{m}, \ell(d) \equiv j \pmod{6}} \mu(d).$$

Therefore (2.39) will follow from (2.42) and from the following lemma. \square

Lemma 2.2. *The integer $T(m, j)$ defined in (2.43) with the convention (2.38) and the definitions (2.18) and (2.24)-(2.27), for $m \neq 1$, is equal to*

$$(2.44) \quad T(m, j) = 2^{\omega_3-1} 3^{\lceil \frac{\omega_2+\omega_4}{2} - 1 \rceil} v_{\alpha-2j} + \frac{0^{\omega_3}}{2} 3^{\lceil \frac{\omega}{2} - 1 \rceil} v_{\alpha-4j} + 0^{\omega_2+\omega_4} \frac{(-1)^j}{3} 2^{\omega-1}.$$

Proof of Lemma 2.2. Let us introduce the polynomial

$$(2.45) \quad f(X) = (1-X)^{\omega_1} (1-X^2)^{\omega_2} \dots (1-X^5)^{\omega_5} = \sum_{\nu \geq 0} f_\nu X^\nu.$$

If the five signs were plus instead of minus, $f(X)$ would be the generating function of the partitions in at most ω_1 parts equal to 1, ..., at most ω_5 parts equal to 5. More generally, the polynomial

$$\tilde{f}(X) = \prod_{i=1}^{\omega} (1 + a_i X^{b_i}) = \sum_{\nu \geq 0} \tilde{f}_\nu X^\nu$$

is the generating function of

$$\tilde{f}_\nu = \sum_{\epsilon_1, \dots, \epsilon_\omega \in \{0,1\}, \sum_{i=1}^{\omega} \epsilon_i b_i = \nu} \prod_{i=1}^{\omega} a_i^{\epsilon_i}.$$

To the vector $\epsilon = (\epsilon_1, \dots, \epsilon_\omega) \in \mathbb{F}_2^\omega$, we associate

$$d = \prod_{i=1}^{\omega} p_i^{\epsilon_i}, \quad \mu(d) = \prod_{i=1}^{\omega} (-1)^{\epsilon_i}, \quad L(d) = \sum_{i=1}^{\omega} \epsilon_i \ell(p_i)$$

where L is the arithmetic function defined by (2.17) and we get

$$(2.46) \quad f_\nu = \sum_{d|\bar{m}, L(d)=\nu} \mu(d).$$

Consequently, by setting $\xi = \exp(\frac{i\pi}{3})$, (2.43), (2.45) and (2.46) give

$$\begin{aligned} T(m, j) &= \sum_{\nu, \nu \equiv j \pmod{6}} \sum_{d|\bar{m}, L(d)=\nu} \mu(d) \\ &= \sum_{\nu \equiv j \pmod{6}} f_\nu \\ &= \frac{1}{6} \sum_{i=0}^5 \xi^{-ij} f(\xi^i) \\ &= \frac{1}{6} \sum_{i=1}^5 \xi^{-ij} f(\xi^i) \\ (2.47) \quad &= \frac{1}{6} \sum_{i=1}^5 \xi^{-ij} (1 - \xi^i)^{\omega_1} (1 - \xi^{2i})^{\omega_2} (1 - \xi^{3i})^{\omega_3} (1 - \xi^{4i})^{\omega_4} (1 - \xi^{5i})^{\omega_5}. \end{aligned}$$

By observing that

$$1 - \xi = \xi^5, \quad 1 - \xi^2 = \varrho = \sqrt{3}(\cos \frac{\pi}{6} - i \sin \frac{\pi}{6}), \quad 1 - \xi^3 = 2, \quad 1 - \xi^4 = \bar{\varrho}, \quad 1 - \xi^5 = 0,$$

the sum of the terms in $i = 1$ and $i = 5$ in (2.47), which are conjugate, is equal to

$$(2.48) \quad \frac{2}{6} \mathcal{R}(\xi^{-j} \xi^{5\omega_1} \varrho^{\omega_2} \bar{\varrho}^{\omega_3} \varrho^{\omega_4} \xi^{\omega_5}) = \frac{2^{\omega_3}}{3} \sqrt{3}^{\omega_2 + \omega_4} \cos \frac{\pi}{6} (2\omega_5 - 2\omega_1 + \omega_4 - \omega_2 - 2j).$$

Now, the contribution of the terms in $i = 2$ and $i = 4$ is

$$\begin{aligned} (2.49) \quad \frac{2}{6} \mathcal{R}(\xi^{-2j} \varrho^{\omega_1} \bar{\varrho}^{\omega_2} 0^{\omega_3} \varrho^{\omega_4} \bar{\varrho}^{\omega_5}) &= 0^{\omega_3} \frac{\sqrt{3}^{\omega_1 + \omega_2 + \omega_4 + \omega_5}}{3} \\ &\quad \times \cos \frac{\pi}{6} (\omega_2 + \omega_5 - \omega_1 - \omega_4 - 4j) \\ &= 0^{\omega_3} \frac{\sqrt{3}^\omega}{3} \cos \frac{\pi}{6} (\omega_2 + \omega_5 - \omega_1 - \omega_4 - 4j). \end{aligned}$$

Finally, the term corresponding to $i = 3$ in (2.47) is equal to

$$(2.50) \quad \frac{1}{6} (-1)^j 2^{\omega_1} 0^{\omega_2} 2^{\omega_3} 0^{\omega_4} 2^{\omega_5} = 0^{\omega_2 + \omega_4} \frac{(-1)^j}{6} 2^{\omega_1 + \omega_3 + \omega_5} = 0^{\omega_2 + \omega_4} \frac{(-1)^j}{6} 2^\omega.$$

Consequently, by using our notation (2.24)-(2.26), (2.47) becomes

$$T(m, j) = \frac{2^{\omega_3}}{3} \sqrt{3}^{\omega_2 + \omega_4} \cos \frac{\pi}{6} (\alpha - 2j) + 0^{\omega_3} \frac{\sqrt{3}^\omega}{3} \cos \frac{\pi}{6} (a - 4j)$$

$$(2.51) \quad + 0^{\omega_2 + \omega_4} \frac{(-1)^j}{6} 2^\omega.$$

Observing that $\alpha - 2j$ has the same parity than $\omega_2 + \omega_4$ and similarly for $a - 4j$ and ω (when $\omega_0 = \omega_3 = 0$), via (2.27), we get (2.44). \square

Proof of Theorem 2.2 (2). For all $k \geq 0$, from (1.10), we have

$$\begin{aligned} (2.52) \quad 31mS_{\mathcal{A}}(31m, k) &= \sum_{d|31m} \mu(d) \sigma(\mathcal{A}, 31 \cdot 2^k \frac{m}{d}) = \sum_{d|31\bar{m}} \mu(d) \sigma(\mathcal{A}, 31 \cdot 2^k \frac{m}{d}) \\ &= \sum_{d|\bar{m}} \mu(d) \sigma(\mathcal{A}, 31 \cdot 2^k \frac{m}{d}) - \sum_{d|\bar{m}} \mu(d) \sigma(\mathcal{A}, 2^k \frac{m}{d}) \\ &= \sum_{d|\bar{m}} \mu(d) \sigma(\mathcal{A}, 31 \cdot 2^k \frac{m}{d}) - mS_{\mathcal{A}}(m, k). \end{aligned}$$

Since for all d dividing \bar{m} , $31 \cdot 2^k \frac{m}{d} \in O(31)$ then, from (2.23), $\sigma(\mathcal{A}, 31 \cdot 2^k \frac{m}{d}) \equiv \sigma(\mathcal{A}, 31 \cdot 2^k) \equiv -5 \pmod{2^{k+1}}$, so that (2.52) gives

$$(2.53) \quad 31mS_{\mathcal{A}}(31m, k) + mS_{\mathcal{A}}(m, k) \equiv -5 \sum_{d|\bar{m}} \mu(d) \pmod{2^{k+1}}.$$

Since $\bar{m} \neq 1$, $31mS_{\mathcal{A}}(31m, k) + mS_{\mathcal{A}}(m, k) \equiv 0 \pmod{2^{k+1}}$. Recalling that m is odd, by using (2.20), (2.21) and their similar for $S(31m)$, we obtain the desired result. \square

3. Elements of the set $\mathcal{A} = \mathcal{A}(1 + z + z^3 + z^4 + z^5)$.

In this section, we will determine the elements of the set \mathcal{A} of the form $n = 2^k 31^\tau m$, where $\bar{m} \neq 1$ satisfies (2.24) and $\tau \in \{0, 1\}$, since from Remark 2.2, $2^k 31^\tau m \notin \mathcal{A}$ for all $\tau \geq 2$. The elements of the set $\mathcal{A}(1 + z + z^3 + z^4 + z^5)$ of the form $31^\tau 2^k$, $\tau = 0$ or 1 , were shown in [1] to be solutions of 2-adic equations. More precisely, the following was proved in that paper.

1) The elements of the set $\mathcal{A}(1 + z + z^3 + z^4 + z^5)$ of the form 2^k , $k \geq 0$, are given by the 2-adic solution

$$\sum_{k \geq 0} \chi(\mathcal{A}, 2^k) 2^k = S(1) = U_0 = 1 + 2 + 2^2 + 2^3 + 2^4 + 2^7 + 2^{10} + 2^{11} + \dots$$

of the equation

$$y^6 - y^5 + 3y^4 - 11y^3 + 44y^2 - 36y + 32 = 0.$$

Note that $S(1) = U_0$ follows from (2.22).

2) The elements of the set $\mathcal{A}(1 + z + z^3 + z^4 + z^5)$ of the form $31 \cdot 2^k$, $k \geq 0$, are given by the solution

$$\sum_{k \geq 0} \chi(\mathcal{A}, 31 \cdot 2^k) 2^k = S(31) = y = 2^2 + 2^5 + 2^{11} + \dots$$

of the equation

$$31^5 y^6 + 31^5 y^5 + 13 \cdot 31^4 y^4 + 91 \cdot 31^3 y^3 + 364 \cdot 31^2 y^2 + 796 \cdot 31 y + 752 = 0,$$

since, from (2.53) with $m = 1$, we have $31S(31) = -5 - U_0$, so that

$$S(31) = \frac{5 + U_0}{1 - 32} = (1 + 4 + U_0)(1 + 2^5 + 2^{10} + \dots) = 2^2 + 2^5 + 2^{11} + \dots$$

Theorem 3.1. *Let $m \neq 1$ be an odd integer not divisible by any prime $p \in \mathcal{P}_0$ (cf. (2.16)) neither by 31^2 . Then the sum $S(m)$ defined by (2.20) does not vanish. So we may introduce the 2-adic valuation of $S(m)$:*

$$(3.1) \quad \gamma = \gamma(m) = v_2(S(m)).$$

Then, if 31 does not divide m , we have

$$(3.2) \quad \gamma(31m) = \gamma(m).$$

Let us assume now that m is coprime with 31. We shall use the quantities $\omega_i = \omega_i(m)$ defined by (2.18), $\ell(m)$, $\alpha = \alpha(m)$, $a = a(m)$ defined by (2.15), (2.25) and (2.26),

$$(3.3) \quad \alpha' = \alpha'(m) = \alpha - 2\ell(m) \pmod{12} = 2\omega_5 - 2\omega_1 + \omega_4 - \omega_2 - 2\ell(m) \pmod{12},$$

$$(3.4) \quad a' = a'(m) = a - 4\ell(m) \pmod{12} = \omega_5 - \omega_1 + \omega_2 - \omega_4 - 4\ell(m) \pmod{12},$$

$$(3.5) \quad t = t(m) = \left\lfloor \frac{\omega_1 + \omega_5 + \omega_2 + \omega_4}{2} - 1 \right\rfloor - \left\lfloor \frac{\omega_2 + \omega_4}{2} - 1 \right\rfloor = \begin{cases} \left\lfloor \frac{\omega_1 + \omega_5}{2} \right\rfloor & \text{if } \omega_1 + \omega_5 \equiv \omega_2 + \omega_4 \equiv 1 \pmod{2} \\ \left\lfloor \frac{\omega_1 + \omega_5}{2} - 1 \right\rfloor & \text{if not.} \end{cases}$$

We have:

(i) if $\omega_3 \neq 0$ and $\omega_2 + \omega_4 \neq 0$, the value of $\gamma = \gamma(m)$ is given by

$$\gamma = \begin{cases} \omega_3 - 1 & \text{if } \alpha' \equiv 0, 1, 3, 4 \pmod{6} \\ \omega_3 & \text{if } \alpha' \equiv 2 \pmod{6} \\ \omega_3 + 2 & \text{if } \alpha' \equiv 5 \pmod{6}. \end{cases}$$

(ii) If $\omega_2 + \omega_4 = 0$ and $\omega_3 \geq 1$, we set $\alpha'' = \alpha' + 6\ell(m) \pmod{12}$ and $\delta(i) = v_2(E_i + 2^{v_2(E_i)}G)$ and we have

$$\begin{aligned} \text{if } \omega_1 + \omega_5 < v_2(E_{\alpha''}), & \text{ then } \gamma = \omega_3 - 1 + \omega_1 + \omega_5, \\ \text{if } \omega_1 + \omega_5 = v_2(E_{\alpha''}), & \text{ then } \gamma = \omega_3 - 1 + \delta(\alpha''), \\ \text{if } \omega_1 + \omega_5 > v_2(E_{\alpha''}), & \text{ then } \gamma = \omega_3 - 1 + v_2(E_{\alpha'').} \end{aligned}$$

(iii) If $\omega_3 = 0$ and $\omega_2 + \omega_4 \neq 0$, we have

$$\gamma = -1 + v_2(E_{\alpha'} + 3^t F_{\alpha'}).$$

(iv) If $\omega_3 = \omega_2 = \omega_4 = 0$ and $\omega_1 + \omega_5 \neq 0$, we have

$$\gamma = -1 + v_2(E_{\alpha'} + 3^t F_{\alpha'} + 2^{\omega_1 + \omega_5} (-1)^{\ell(m)} G).$$

Proof. We shall prove that $S(m) \neq 0$ in each of the four cases above. Assuming $S(m) \neq 0$, it follows from Theorem 2.2, (2) that $S(31m) \neq 0$ and that $\gamma(31m) = \gamma(m)$, which sets (3.2).

Proof of Theorem 3.1 (i). In this case, formula (2.39) reduces to

$$mS(m) = 2^{\omega_3 - 1} 3^{\left\lfloor \frac{\omega_2 + \omega_4}{2} - 1 \right\rfloor} E_{\alpha'}.$$

Since $E_{\alpha'} \neq 0$, $S(m)$ does not vanish; we have

$$\gamma = v_2(S(m)) = \omega_3 - 1 + v_2(E_{\alpha'})$$

and the result follows from the values of $E_{\alpha'}$ modulo 2^{11} given in Table 1.

Proof of Theorem 3.1 (ii). If $\omega_2 + \omega_4 = 0$ and $\omega_3 \neq 0$, formula (2.39) becomes (since, cf. (2.35), $E_{i+6} = -E_i$ holds)

$$\begin{aligned} mS(m) &= \frac{2^{\omega_3 - 1}}{3} (E_{\alpha'} + 2^{\omega_1 + \omega_5} (-1)^{\ell(m)} G) \\ &= (-1)^{\ell(m)} \frac{2^{\omega_3 - 1}}{3} (E_{\alpha''} + 2^{\omega_1 + \omega_5} G). \end{aligned}$$

As displayed in Table 1, E_i is a linear combination of E_0 and E_1 so that, from Lemma 2.1, $S(m)$ does not vanish and $\gamma = \omega_3 - 1 + v_2(E_{\alpha''} + 2^{\omega_1 + \omega_5} G)$, whence the result. The values of $v_2(E_i)$ and $\delta(i)$ calculated from Table 1 are given below.

i	0	1	2	3	4	5	6	7	8	9	10	11
$v_2(E_i)$	0	0	1	0	0	3	0	0	1	0	0	3
$\delta(i)$	1	1	2	1	1	8	2	2	4	2	2	4

Proof of Theorem 3.1 (iii). If $\omega_3 = 0$ and $\omega_2 + \omega_4 \neq 0$ it follows, from (2.39) and the definition of t above, that

$$mS(m) = \frac{1}{2} 3^{\left\lfloor \frac{\omega_2 + \omega_4}{2} - 1 \right\rfloor} (E_{\alpha'} + 3^t F_{\alpha'}).$$

But E_i and F_i are non-zero linear combinations of, respectively, E_0 and E_1 and F_0 and F_1 ; by Lemma 2.1, $E_{\alpha'} + 3^t F_{\alpha'}$ does not vanish and $\gamma = -1 + v_2(E_{\alpha'} + 3^t F_{\alpha'})$.

Proof of Theorem 3.1 (iv). If $\omega_3 = \omega_2 = \omega_4 = 0$ and $m \neq 1$, formula (2.39) gives

$$mS(m) = \frac{1}{6} (E_{\alpha'} + 3^t F_{\alpha'} + 2^{\omega_1 + \omega_5} (-1)^{\ell(m)} G).$$

From Lemma 2.1, we obtain $E_{\alpha'} + 3^t F_{\alpha'} + 2^{\omega_1 + \omega_5} (-1)^{\ell(m)} G \neq 0$, which implies $S(m) \neq 0$ and $\gamma = -1 + v_2(E_{\alpha'} + 3^t F_{\alpha'} + 2^{\omega_1 + \omega_5} (-1)^{\ell(m)} G)$. \square

Theorem 3.2. Let m be an odd integer satisfying $m \neq 1$, $\gcd(m, 31) = 1$, and with \bar{m} of the form (2.24). Let $\gamma = \gamma(m)$ as defined in Theorem 3.1 and $Z(m)$ be the odd part of the right hand-side of (2.39), so that

$$(3.6) \quad mS(m) = 2^{\gamma(m)}Z(m).$$

- (i) If $k < \gamma$, then $2^k m \notin \mathcal{A}$ and $2^k 31m \notin \mathcal{A}$.
- (ii) If $k = \gamma$, then $2^k m \in \mathcal{A}$ and $2^k 31m \in \mathcal{A}$.
- (iii) If $k = \gamma + r$, $r \geq 1$, then we set $S_r = \{2^r + 1, 2^r + 3, \dots, 2^{r+1} - 1\}$ and we have

$$2^{\gamma+r}m \in \mathcal{A} \iff \exists l \in S_r, m \equiv l^{-1}Z(m) \pmod{2^{r+1}},$$

$$2^{\gamma+r}31m \in \mathcal{A} \iff \exists l \in S_r, m \equiv -(31l)^{-1}Z(m) \pmod{2^{r+1}}.$$

Proof of Theorem 3.2, (i). We remind that m is odd and (cf. 2.21) $S(m) \equiv S_{\mathcal{A}}(m, k) \pmod{2^{k+1}}$. It is obvious from (3.6) that if $\gamma > k$ then $S_{\mathcal{A}}(m, k) \equiv 0 \pmod{2^{k+1}}$. So that from (1.8), $S_{\mathcal{A}}(m, k) = 0$ and $2^k m \notin \mathcal{A}$, for all h , $0 \leq h \leq k$. To prove that $2^k 31m \notin \mathcal{A}$, it suffices to use this last result and (2.40) modulo 2^{k+1} .

Proof of Theorem 3.2, (ii). If $\gamma = k$ then the same arguments as above show that

$$mS_{\mathcal{A}}(m, k) \equiv 2^k Z(m) \pmod{2^{k+1}}.$$

So that, by using Theorem 3.2, (i) and (1.8), we obtain

$$2^k m \chi(\mathcal{A}, 2^k m) \equiv 2^k Z(m) \pmod{2^{k+1}}.$$

Since both m and $Z(m)$ are odd, we get $\chi(\mathcal{A}, 2^k m) \equiv 1 \pmod{2}$, which shows that $2^k m \in \mathcal{A}$. Once again, to prove that $2^k 31m \in \mathcal{A}$, it suffices to use this last result and (2.40) modulo 2^{k+1} .

Proof of Theorem 3.2, (iii). Let us set $k = \gamma + r$, $r \geq 1$. (3.6) and (2.21) give

$$(3.7) \quad mS_{\mathcal{A}}(m, k) \equiv 2^{\gamma}Z(m) \pmod{2^{\gamma+r+1}}.$$

So that, by using Theorem 3.2, (i) and (ii), we get

$$m(2^{\gamma+2^{\gamma+1}}\chi(\mathcal{A}, 2^{\gamma+1}m) + \dots + 2^{\gamma+r}\chi(\mathcal{A}, 2^{\gamma+r}m)) \equiv 2^{\gamma}Z(m) \pmod{2^{\gamma+r+1}},$$

which reduces to

$$m(1 + 2\chi(\mathcal{A}, 2^{\gamma+1}m) + \dots + 2^r\chi(\mathcal{A}, 2^{\gamma+r}m)) \equiv Z(m) \pmod{2^{r+1}}.$$

By observing that $2^{\gamma+r}m \in \mathcal{A}$ if and only if $l = 1 + 2\chi(\mathcal{A}, 2^{\gamma+1}m) + \dots + 2^r\chi(\mathcal{A}, 2^{\gamma+r}m)$ is an odd integer in S_r , we obtain

$$2^{\gamma+r}m \in \mathcal{A} \iff m \equiv l^{-1}Z(m) \pmod{2^{r+1}}, l \in S_r.$$

To prove the similar result for $2^{\gamma+r}31m$, one uses the same method and (2.40) modulo 2^{k+1} . \square

4. The counting function.

In Theorem 4.1 below, we will determine an asymptotic estimate to the counting function $A(x)$ (cf. (1.2)) of the set $\mathcal{A} = \mathcal{A}(1 + z + z^3 + z^4 + z^5)$. The following lemmas will be needed.

Lemma 4.1. Let K be any positive integer and $x \geq 1$ be any real number. We have

$$|\{n \leq x : \gcd(n, K) = 1\}| \leq 7 \frac{\varphi(K)}{K} x,$$

where φ is the Euler function.

Proof. This is a classical result from sieve theory: see Theorems 3 – 5 of [11]. \square

Lemma 4.2. (Mertens's formula) Let θ and η be two positive coprime integers. There exists an absolute constant C_1 such that, for all $x > 1$,

$$\pi(x; \theta, \eta) = \prod_{p \leq x, p \equiv \theta \pmod{\eta}} \left(1 - \frac{1}{p}\right) \leq \frac{C_1}{(\log x)^{\frac{1}{\eta}}}.$$

Proof. For θ and η fixed, Mertens's formula follows from the Prime Number Theorem in arithmetic progressions. It is proved in [9] that the constant C_1 is absolute. \square

Lemma 4.3. For $i \in \{2, 3, 4\}$, let

$$K_i = K_i(x) = \prod_{p \leq x, \ell(p) \in \{0, i\}} p = \prod_{p \leq x, p \in \mathcal{P}_0 \cup \mathcal{P}_i} p,$$

where ℓ , \mathcal{P}_0 and \mathcal{P}_i are defined by (2.15)–(2.16). Then for x large enough,

$$|\{n : 1 \leq n \leq x, \gcd(n, K_i) = 1\}| = \mathcal{O}\left(\frac{x}{(\log x)^{\frac{1}{3}}}\right).$$

Proof. By Lemma 4.1 and (2.16), we have

$$\begin{aligned} |\{n : n \leq x, \gcd(n, K_i) = 1\}| &\leq 7x \frac{\varphi(K_i)}{K_i} \\ &= 7x \prod_{0 \leq j \leq 4, \tau \in \{0, i\}} \prod_{p \leq x, p \equiv 2^j 3^\tau \pmod{31}} \left(1 - \frac{1}{p}\right). \end{aligned}$$

So that by Lemma 4.2, for all $i \in \{2, 3, 4\}$ and x large enough,

$$|\{n : n \leq x, \gcd(n, K_i) = 1\}| \leq \frac{7C_1^{10} x}{(\log x)^{\frac{10}{31}}} = \mathcal{O}\left(\frac{x}{(\log x)^{\frac{1}{3}}}\right).$$

\square

Lemma 4.4. Let $r, u \in \mathbb{N}_0$, ℓ and α' be the functions defined by (2.15) and (3.3), ω_j be the additive function given by (2.18). We take ξ to be a Dirichlet character modulo 2^{r+1} with ξ_0 as principal character and we let ϱ be the completely multiplicative function defined on primes p by

$$(4.1) \quad \varrho(p) = \begin{cases} 0 & \text{if } \ell(p) = 0 \text{ or } p = 31 \\ 1 & \text{otherwise.} \end{cases}$$

If y and z are respectively some 2^u -th and 12 -th roots of unity in \mathbb{C} , and if x is a real number > 1 , we set

$$(4.2) \quad S_{y,z,\xi}(x) = \sum_{2^{\omega_3(n)}n \leq x} \varrho(n)\xi(n)y^{\omega_2(n)+\omega_4(n)}z^{\alpha'(n)}.$$

Then, when x tends to infinity, we have

• If $\xi \neq \xi_0$,

$$(4.3) \quad S_{y,z,\xi}(x) = O\left(x \frac{\log \log x}{(\log x)^2}\right).$$

• If $\xi = \xi_0$,

$$(4.4) \quad S_{y,z,\xi_0}(x) = \frac{x}{(\log x)^{1-f_{y,z}(1)}} \left(\frac{H_{y,z,\xi_0}(1)C_{y,z}}{\Gamma(f_{y,z}(1))} + O\left(\frac{\log \log x}{\log x}\right) \right),$$

where Γ is the Euler gamma function,

$$(4.5) \quad f_{y,z}(s) = \frac{5}{\varphi(31)} \sum_{1 \leq j \leq 5} g_{j,y,z}(s),$$

$$(4.6) \quad \begin{aligned} g_{1,y,z}(s) &= z^8, & g_{2,y,z}(s) &= yz^7, & g_{3,y,z}(s) &= \frac{z^6}{2^s}, \\ g_{4,y,z}(s) &= yz^5, & g_{5,y,z}(s) &= z^4, \end{aligned}$$

$$(4.7) \quad H_{y,z,\xi}(s) = \prod_{1 \leq j \leq 5} \prod_{p, \ell(p)=j} \left(1 + \frac{g_{j,y,z}(s)\xi(p)}{p^s - z^{-2j}\xi(p)} \right) \left(1 - \frac{\xi(p)}{p^s} \right)^{g_{j,y,z}(s)},$$

$$(4.8) \quad C_{y,z} = \prod_{1 \leq j \leq 5} \left\{ \prod_{p, \ell(p)=j} \left(1 - \frac{1}{p} \right)^{-g_{j,y,z}(1)} \prod_p \left(1 - \frac{1}{p} \right)^{\frac{g_{j,y,z}(1)}{30}} \right\}.$$

Proof. The evaluation of such sums is based, as we know, on the Selberg-Delange method. In [7], one finds an application towards direct results on such problems. In our case, to apply Theorem 1 of that paper, one should start with expanding, for complex number s with $\Re s > 1$, the Dirichlet series

$$F_{y,z,\xi}(s) = \sum_{n \geq 1} \frac{\varrho(n)\xi(n)y^{\omega_2(n)+\omega_4(n)}z^{\alpha'(n)}}{(2^{\omega_3(n)}n)^s}$$

in an Euler product given by

$$\begin{aligned} F_{y,z,\xi}(s) &= \prod_{1 \leq j \leq 5} \prod_{p, \ell(p)=j} \left(1 + \sum_{m=1}^{\infty} \frac{\xi(p^m)y^{\omega_2(p^m)+\omega_4(p^m)}z^{\alpha'(p^m)}}{(2^{\omega_3(p^m)}p^m)^s} \right) \\ &= \prod_{1 \leq j \leq 5} \prod_{p, \ell(p)=j} \left(1 + \frac{g_{j,y,z}(s)\xi(p)}{p^s - z^{-2j}\xi(p)} \right), \end{aligned}$$

which can be written

$$F_{y,z,\xi}(s) = H_{y,z,\xi}(s) \prod_{1 \leq j \leq 5} \prod_{p, \ell(p)=j} \left(1 - \frac{\xi(p)}{p^s} \right)^{-g_{j,y,z}(s)},$$

where $g_{j,y,z}(s)$ and $H_{y,z,\xi}(s)$ are defined by (4.6) and (4.7). To complete the proof of Lemma 4.4, one has to show that $H_{y,z,\xi}(s)$ is holomorphic for $\Re s > \frac{1}{2}$ and, for y and z fixed, that $H_{y,z,\xi}(s)$ is bounded for $\Re s \geq \sigma_0 > \frac{1}{2}$, which can be done by adapting the method given in [7] (Preuve du Théorème 2, p. 235). \square

Lemma 4.5. We keep the above notation and we let \mathcal{G} be the set of integers of the form $n = 2^{\omega_3(m)}m$ with the following conditions:

- m odd and $\gcd(m, 31) = 1$,
- $m = m_1m_2m_3m_4m_5$, where all prime factors p of m_i satisfy $\ell(p) = i$.

If $G(x)$ is the counting function of the set \mathcal{G} then, when x tends to infinity,

$$(4.9) \quad G(x) = \frac{Cx}{(\log x)^{1/4}} \left(1 + O\left(\frac{\log \log x}{\log x}\right) \right),$$

where

$$(4.10) \quad C = \frac{H_{1,1,\xi_0}(1)C_{1,1}}{\Gamma(f_{1,1}(1))} = 0.61568378\dots,$$

$H_{1,1,\xi_0}(1)$, $C_{1,1}$ and $f_{1,1}(1)$ are defined by (4.7), (4.8) and (4.5).

Proof. We apply Lemma 4.4 with $y = z = 1$, $\xi = \xi_0$ and remark that $G(x) = S_{1,1,\xi_0}(x)$. By observing that $(1 + \frac{1}{p-1})(1 - \frac{1}{p}) = 1$, we have

$$\begin{aligned} H_{1,1,\xi_0}(1) &= \prod_{p \in \mathcal{P}_3} \left(1 + \frac{1}{2(p-1)} \right) \left(1 - \frac{1}{p} \right)^{\frac{1}{2}} = \prod_{p \in \mathcal{P}_3} \left(1 - \frac{1}{2p} \right) \left(1 - \frac{1}{p} \right)^{-\frac{1}{2}} \\ &\approx 1.000479390466, \end{aligned}$$

$$C_{1.1} = \lim_{x \rightarrow \infty} \prod_{\substack{p \in \mathcal{P}_1 \cup \mathcal{P}_2 \cup \mathcal{P}_4 \cup \mathcal{P}_5, \\ p \leq x}} \left(1 - \frac{1}{p}\right)^{-1} \prod_{\substack{p \in \mathcal{P}_3, \\ p \leq x}} \left(1 - \frac{1}{p}\right)^{-\frac{1}{2}} \prod_{p \leq x} \left(1 - \frac{1}{p}\right)^{\frac{3}{4}} \\ \approx 0.75410767606.$$

The numerical value of the above Eulerian products has been computed by the classical method already used and described in [7]. Since $\Gamma(f_{1,1}(1)) = \Gamma(\frac{3}{4}) = 1.225416702465\dots$, we get (4.10). \square

Lemma 4.6. *We keep the notation introduced in Lemmas 4.4 and 4.5. If $(y, z) \in \{(1, 1), (-1, -1)\}$, we have*

$$(4.11) \quad S_{y,z,\xi_0}(x) = \frac{Cx}{(\log x)^{1/4}} \left(1 + \mathcal{O}\left(\frac{\log \log x}{\log x}\right)\right),$$

while, if $(y, z, \xi) \notin \{(1, 1, \xi_0), (-1, -1, \xi_0)\}$, we have

$$(4.12) \quad S_{y,z,\xi}(x) = \mathcal{O}_r \left(\frac{x}{(\log x)^{1/4+2^{-2u-3}}} \right).$$

Proof. For $y = z = 1$, Formula (4.11) follows from Lemma 4.5. For $y = z = -1$ (which does not occur for $u = 0$), it follows from (4.4) and by observing that the values of $g_{j,y,z}(s), f_{y,z}(s), H_{y,z,\xi}(s), C_{y,z}$ do not change when replacing y by $-y$ and z by $-z$.

Let us define

$$M_{y,z} = \Re(f_{y,z}(1)) = \frac{1}{6} \Re(z^6(z^2 + z^{-2} + \frac{1}{2} + y(z + z^{-1}))).$$

When $\xi \neq \xi_0$, (4.3) implies (4.12) while, if $\xi = \xi_0$, it follows from (4.4) and from the inequality to be proved

$$(4.13) \quad M_{y,z} \leq \frac{3}{4} - \frac{1}{2^{2u+3}}, \quad (y, z) \notin \{(1, 1), (-1, -1)\}.$$

To show (4.13), let us first recall that z is a twelfth root of unity.

If $z \neq \pm 1$, $6f_{y,z}(1)$ is equal to one of the numbers $-3/2 \pm y\sqrt{3}, -1/2 \pm y, 3/2$ so that

$$M_{y,z} \leq |f_{y,z}(1)| \leq \frac{1}{6} \left(\frac{3}{2} + \sqrt{3} \right) < 0.55 \leq \frac{3}{4} - \frac{1}{2^{2u+3}}$$

for all $u \geq 0$, which proves (4.13).

If $z = 1$ and $y \neq 1$ (which implies $u \geq 1$), we have

$$\Re y \leq \cos \frac{2\pi}{2u} = 1 - 2 \sin^2 \frac{\pi}{2u} \leq 1 - 2 \left(\frac{2\pi}{\pi 2u} \right)^2 = 1 - \frac{8}{2^{2u}},$$

and

$$M_{y,1} = \frac{5}{12} + \frac{1}{3} \Re y \leq \frac{3}{4} - \frac{8}{3 \cdot 2^{2u}} < \frac{3}{4} - \frac{1}{2^{2u+3}}.$$

If $z = -1$ and $y \neq -1$, (4.13) follows from the preceding case by observing that $f_{y,z}(1) = f_{-y,-z}(1)$, which completes the proof of (4.13). \square

Lemma 4.7. *Let \mathcal{G} be the set defined in Lemma 4.5, ω_j and α' be the functions given by (2.18) and (3.3). For $0 \leq j \leq 11$, $r, u, \lambda, t \in \mathbb{N}_0$ such that t is odd, we let $\mathcal{G}_{j,r,u,\lambda,t}$ be the set of integers $n = 2^{u_3(m)}m$ in \mathcal{G} with the following conditions:*

- $\alpha'(m) \equiv j \pmod{12}$,
- $\omega_2(m) + \omega_4(m) \equiv \lambda \pmod{2^u}$,
- $m \equiv t \pmod{2^{r+1}}$.

If ρ is the function given by (4.1), the counting function $G_{j,r,u,\lambda,t}(x)$ of the set $\mathcal{G}_{j,r,u,\lambda,t}$ is equal to

$$G_{j,r,u,\lambda,t}(x) = \sum_{\substack{2^{u_3(m)}m \leq x, m \equiv t \pmod{2^{r+1}} \\ \alpha'(m) \equiv j \pmod{12}, \omega_2(m) + \omega_4(m) \equiv \lambda \pmod{2^u}}} \rho(m).$$

If $u \geq 1$ and $\lambda \not\equiv j \pmod{2}$, $\mathcal{G}_{j,r,u,\lambda,t}$ is empty while, if $\lambda \equiv j \pmod{2}$, when x tends to infinity, we have

$$G_{j,r,u,\lambda,t}(x) = \frac{C}{6 \cdot 2^{r+u}} \frac{x}{(\log x)^{\frac{1}{4}}} \left(1 + \mathcal{O}\left(\frac{1}{(\log x)^{2^{-2u-3}}}\right)\right),$$

where C is the constant given by (4.10).

If $u = 0$, then

$$G_{j,r,0,0,t}(x) = \frac{C}{12 \cdot 2^r} \frac{x}{(\log x)^{\frac{1}{4}}} \left(1 + \mathcal{O}\left(\frac{1}{(\log x)^{1/8}}\right)\right),$$

Proof. If $u \geq 1$, it follows from (3.3) that $\alpha'(m) \equiv \omega_2(m) + \omega_4(m) \pmod{2}$; therefore, if $j \not\equiv \lambda \pmod{2}$, then $\mathcal{G}_{j,r,u,\lambda,t}$ is empty. Let us set

$$\zeta = e^{\frac{2i\pi}{2^u}}, \quad \mu = e^{\frac{2i\pi}{12}}.$$

By using the relations of orthogonality:

$$\sum_{j_2=0}^{11} \mu^{j_2 \alpha'(m)} \mu^{-j j_2} = \begin{cases} 12 & \text{if } \alpha' \equiv j \pmod{12} \\ 0 & \text{if not,} \end{cases}$$

$$\sum_{j_1=0}^{2^u-1} \zeta^{-\lambda j_1} \zeta^{j_1(\omega_2(m) + \omega_4(m))} = \begin{cases} 2^u & \text{if } \omega_2(m) + \omega_4(m) \equiv \lambda \pmod{2^u} \\ 0 & \text{if not,} \end{cases}$$

$$\sum_{\xi \pmod{2^{r+1}}} \bar{\xi}(t) \xi(m) = \begin{cases} \varphi(2^{r+1}) = 2^r & \text{if } m \equiv t \pmod{2^{r+1}} \\ 0 & \text{if not,} \end{cases}$$

we get

$$G_{j,r,u,\lambda,t}(x) = \frac{1}{12 \cdot 2^{r+u}} \sum_{\xi \pmod{2^{r+1}}} \sum_{j_1=0}^{2^u-1} \sum_{j_2=0}^{11} \bar{\xi}(t) \zeta^{-\lambda j_1} \mu^{-j j_2} S_{\zeta^{j_1} \mu^{j_2}, \xi}(x).$$

In the above triple sums, the main contribution comes from $S_{1,1,\xi_0}(x)$ and $S_{-1,-1,\xi_0}(x)$, and the result follows from (4.11) and (4.12).

If $u = 0$, we have

$$G_{j,r,0,0,t}(x) = \frac{1}{12 \cdot 2^r} \sum_{\xi \bmod 2^{r+1}} \sum_{j_2=0}^{11} \bar{\xi}(t) \mu^{-jj_2} S_{1,\mu^{j_2},\xi}(x)$$

and, again, the result follows from Lemma 4.6. \square

Theorem 4.1. *Let $\mathcal{A} = \mathcal{A}(1 + z + z^3 + z^4 + z^5)$ be the set given by (1.3) and $A(x)$ be its counting function. When $x \rightarrow \infty$, we have*

$$A(x) \sim \kappa \frac{x}{(\log x)^{\frac{1}{4}}},$$

where $\kappa = \frac{74}{31}C = 1.469696766\dots$ and C is the constant of Lemma 4.5 defined by (4.10).

Proof. Let us define the sets $\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3$ and \mathcal{A}_4 containing the elements $n = 2^k m$ (m odd) of \mathcal{A} with the restrictions:

$$\begin{aligned} \mathcal{A}_1 : & \omega_3(m) \neq 0 \text{ and } \omega_2(m) + \omega_4(m) \neq 0 \\ \mathcal{A}_2 : & \omega_3(m) \neq 0 \text{ and } \omega_2(m) = \omega_4(m) = 0 \\ \mathcal{A}_3 : & \omega_3(m) = 0 \text{ and } \omega_2(m) + \omega_4(m) \neq 0 \\ \mathcal{A}_4 : & \omega_2(m) = \omega_3(m) = \omega_4(m) = 0. \end{aligned}$$

We have

$$(4.14) \quad A(x) = A_1(x) + A_2(x) + A_3(x) + A_4(x).$$

Further, for $i = 2, 3, 4$, it follows from Lemma 4.3 that $A_i(x) = \mathcal{O}\left(\frac{x}{(\log x)^{\frac{1}{3}}}\right)$ and therefore

$$(4.15) \quad A(x) = A_1(x) + \mathcal{O}\left(\frac{x}{(\log x)^{\frac{1}{3}}}\right).$$

Now, we split \mathcal{A}_1 in two parts \mathcal{B} and $\widehat{\mathcal{B}}$ by putting in \mathcal{B} the elements $n \in \mathcal{A}_1$ which are coprime with 31 and in $\widehat{\mathcal{B}}$ the elements $n \in \mathcal{A}_1$ which are multiples of 31. Let us recall that, from Remark 2.2, no element of \mathcal{A} is a multiple of 31^2 . Therefore,

$$(4.16) \quad A_1(x) = \mathcal{B}(x) + \widehat{\mathcal{B}}(x)$$

with

$$(4.17) \quad \mathcal{B}(x) = \sum_{n=2^k m \in \mathcal{A}_1, n \leq x} \rho(m), \quad \widehat{\mathcal{B}}(x) = \sum_{n=2^k 31m \in \mathcal{A}_1, n \leq x} \rho(m).$$

Let us consider $\mathcal{B}(x)$; the case of $\widehat{\mathcal{B}}$ will be similar. We define

$$(4.18) \quad \nu_i = \nu_2(E_i) - 1 = \begin{cases} -1 & \text{if } i \equiv 0, 1, 3, 4 \pmod{6} \\ 0 & \text{if } i \equiv 2 \pmod{6} \\ 2 & \text{if } i \equiv 5 \pmod{6} \end{cases}$$

so that, if \widehat{E}_i is the odd part of E_i (cf. (2.32) and Table 1), we have

$$(4.19) \quad \widehat{E}_i = 2^{-1-\nu_i} E_i.$$

In view of Theorem 3.1 (i), if $i = \alpha'(m) \bmod 12$ then

$$(4.20) \quad \gamma(m) - \omega_3(m) = \nu_i.$$

Further, an element $n = 2^k m$ (m odd) belonging to \mathcal{A}_1 is said of index $r \geq 0$ if $k = \gamma(m) + r$. For $r \geq 0$ and $0 \leq i \leq 11$,

$$(4.21) \quad T_r^{(i)}(x) = \sum_{\substack{n=2^{\gamma(m)+r} m \in \mathcal{A}_1, n \leq x \\ \alpha'(m) \equiv i \pmod{12}}} \rho(m) = \sum_{\substack{n=2^{\gamma(m)+r} m \in \mathcal{A}_1, 2^{\omega_3(m)} m \leq 2^{-r-\nu_i} x \\ \alpha'(m) \equiv i \pmod{12}}} \rho(m)$$

will count the number of elements of \mathcal{A}_1 up to x of index r and satisfying $\alpha'(m) \equiv i \pmod{12}$, so that

$$(4.22) \quad \mathcal{B}(x) = \sum_{r \geq 0} \sum_{i=0}^{11} T_r^{(i)}(x).$$

Since $\gamma(m) \geq 0$, from the first equality in (4.21), each n counted in $T_r^{(i)}(x)$ is a multiple of 2^r , hence the trivial upper bound

$$(4.23) \quad \sum_{i=0}^{11} T_r^{(i)}(x) \leq \frac{x}{2^r}.$$

Since $\nu_i \geq -1$, the second equality in (4.21) implies

$$(4.24) \quad \sum_{i=0}^{11} T_r^{(i)}(x) \leq G(2^{1-r} x)$$

with G defined in Lemma 4.5. Moreover, from Lemma 4.5, there exists an absolute constant K such that, for $x \geq 3$,

$$(4.25) \quad G(x) \leq K \frac{x}{(\log x)^{\frac{1}{4}}}.$$

Now, let R be a large but fixed integer; R' is defined in terms of x by $2^{R'-1} \leq \sqrt{x} < 2^{R'}$ and $R'' = \frac{\log x}{\log 2}$. Since $T_r^{(i)}(x)$ is a non-negative integer,

(4.23) implies that $T_r^{(i)}(x) = 0$ for $r > R^n$. If x is large enough, $R < R' < R''$ holds. Setting

$$(4.26) \quad \mathcal{B}_R(x) = \sum_{r=0}^R \sum_{i=0}^{11} T_r^{(i)}(x),$$

from (4.22), we have

$$\mathcal{B}(x) - \mathcal{B}_R(x) = S' + S''$$

with

$$S' = \sum_{r=R+1}^{R'} \sum_{i=0}^{11} T_r^{(i)}(x), \quad S'' = \sum_{r=R'+1}^{R''} \sum_{i=0}^{11} T_r^{(i)}(x).$$

The definition of R' and (4.23) yield

$$S'' \leq \sum_{r=R'+1}^{R''} \frac{x}{2^r} \leq \sum_{r=R'+1}^{\infty} \frac{x}{2^r} = \frac{x}{2^{R'}} \leq \sqrt{x},$$

while (4.24), (4.25) and the definition of R' give

$$\begin{aligned} S' &\leq \sum_{r=R+1}^{R'} G\left(\frac{x}{2^{r-1}}\right) \leq \sum_{r=R+1}^{R'} \frac{2Kx}{2^r \left(\log \frac{x}{2^{r-1}}\right)^{\frac{1}{4}}} \\ &\leq \frac{2^{\frac{3}{4}} Kx}{(\log x)^{\frac{1}{4}}} \sum_{r=R+1}^{R'} \frac{1}{2^r} \leq \frac{3Kx}{2^R (\log x)^{\frac{1}{4}}}, \end{aligned}$$

so that, for x large enough, we have

$$(4.27) \quad 0 \leq \mathcal{B}(x) - \mathcal{B}_R(x) \leq \sqrt{x} + \frac{3Kx}{2^R (\log x)^{\frac{1}{4}}}.$$

We now have to evaluate $T_r^{(i)}(x)$; we shall distinguish two cases, $r = 0$ and $r \geq 1$.

Calculation of $T_0^{(i)}(x)$.

From (4.21), we have

$$T_0^{(i)}(x) = \sum_{\substack{n=2^{\gamma(m)}m \in \mathcal{A}_1, n \leq x \\ \alpha'(m) \equiv i \pmod{12}}} \rho(m) = \sum_{\substack{n=2^{\gamma(m)}m \in \mathcal{A}, n \leq x, \omega_3 \neq 0, \omega_2 + \omega_4 \neq 0 \\ \alpha'(m) \equiv i \pmod{12}}} \rho(m).$$

From Theorem 3.2, we know that $2^{\gamma(m)}m \in \mathcal{A}$. Hence,

$$T_0^{(i)}(x) = \sum_{\substack{2^{\gamma(m)}m \leq x, \omega_3 \neq 0, \omega_2 + \omega_4 \neq 0 \\ \alpha'(m) \equiv i \pmod{12}}} \rho(m),$$

which, by use of (4.20), gives

$$T_0^{(i)}(x) = \sum_{\substack{2^{\omega_3(m)}m \leq 2^{-\nu_i}x, \omega_3 \neq 0, \omega_2 + \omega_4 \neq 0 \\ \alpha'(m) \equiv i \pmod{12}}} \rho(m).$$

But, at the cost of an error term $\mathcal{O}\left(\frac{x}{(\log x)^{\frac{1}{3}}}\right)$, Lemma 4.3 allows us to remove the conditions $\omega_3 \neq 0, \omega_2 + \omega_4 \neq 0$, and to get from the second part of Lemma 4.7,

$$(4.28) \quad \begin{aligned} T_0^{(i)}(x) &= G_{i,0,0,0,1}\left(\frac{x}{2^{\nu_i}}\right) + \mathcal{O}\left(\frac{x}{(\log x)^{\frac{1}{3}}}\right) \\ &= \frac{C}{12} \frac{x}{2^{\nu_i} (\log x)^{\frac{1}{4}}} \left(1 + \mathcal{O}\left(\frac{1}{(\log x)^{1/12}}\right)\right). \end{aligned}$$

Calculation of $T_r^{(i)}(x)$ for $r \geq 1$.

Under the conditions $\omega_3 \neq 0$ and $\omega_2 + \omega_4 \neq 0$, from (3.6), (2.39), (3.3), (4.19) and (4.20), we get

$$Z(m) = 3^{\lceil \frac{\omega_2 + \omega_4}{2} - 1 \rceil} \widehat{E}_{\alpha'(m)}.$$

From (4.21), it follows that

$$T_r^{(i)}(x) = \sum_{\substack{n=2^{\gamma(m)+r}m \in \mathcal{A}, n \leq x, \omega_3 \neq 0, \omega_2 + \omega_4 \neq 0 \\ \alpha'(m) \equiv i \pmod{12}}} \rho(m).$$

Now, by Theorem 3.2, we know that $2^{\gamma(m)+r}m$ belongs to \mathcal{A} if there is some $l \in \mathcal{S}_r = \{2^r + 1, \dots, 2^{r+1} - 1\}$ such that $m \equiv l^{-1}Z(m) \pmod{2^{r+1}}$. Note that the order of 3 modulo 2^{r+1} is 2^{r-1} if $r \geq 2$ and 2^r if $r = 1$. We choose

$$u = r + 1$$

so that $\omega_2 + \omega_4 \equiv \lambda \pmod{2^{r+1}}$ implies $3^{\lceil \frac{\lambda}{2} - 1 \rceil} \equiv 3^{\lceil \frac{\omega_2 + \omega_4}{2} - 1 \rceil} \pmod{2^{r+1}}$. Therefore, we have

$$T_r^{(i)}(x) = \sum_{l \in \mathcal{S}_r} \sum_{\lambda=0}^{2^{r+1}-1} \sum_{\substack{2^{\omega_3(m)}m \leq 2^{-\nu_i-r}x, \omega_3 \neq 0, \omega_2 + \omega_4 \neq 0 \\ \alpha'(m) \equiv i \pmod{12}, \omega_2 + \omega_4 \equiv \lambda \pmod{2^{r+1}} \\ m \equiv l^{-1}3^{\lceil \frac{\lambda}{2} - 1 \rceil} \widehat{E}_i \pmod{2^{r+1}}}} \rho(m).$$

As in the case $r = 0$, we can remove the conditions $\omega_3 \neq 0$ and $\omega_2 + \omega_4 \neq 0$ in the last sum by adding a $\mathcal{O}\left(\frac{x}{(\log x)^{\frac{1}{3}}}\right)$ error term, and we get by Lemma 4.7

for r fixed

$$T_r^{(i)}(x) = \sum_{l \in \mathcal{S}_r} \sum_{\substack{\lambda=0 \\ \lambda \equiv i \pmod{2}}}^{2^{r+1}-1} G_{i,r,r+1,\lambda,l-1} 3^{\lfloor \frac{l}{2} - 1 \rfloor} \widehat{E}_i \left(\frac{x}{2^{\nu_i+r}} \right) + \mathcal{O} \left(\frac{x}{(\log x)^{\frac{1}{3}}} \right)$$

$$(4.29) \quad = \frac{C}{24} \frac{x}{2^{\nu_i+r} (\log x)^{\frac{1}{4}}} \left(1 + \mathcal{O} \left(\frac{1}{(\log x)^{2-2r-5}} \right) \right).$$

From (4.26), (4.28), (4.29) and (4.18), we have

$$B_R(x) = \frac{Cx}{12(\log x)^{\frac{1}{4}}} \left(\left(\sum_{i=0}^{11} \frac{1}{2^{\nu_i}} \right) \left(1 + \frac{1}{2} \sum_{r=1}^R \frac{1}{2^r} \right) + \mathcal{O} \left(\frac{1}{(\log x)^{2-2R-5}} \right) \right)$$

$$= \frac{37}{24} \frac{Cx}{(\log x)^{\frac{1}{4}}} \left(\frac{3}{2} - \frac{1}{2R} \right) \left(1 + \mathcal{O} \left(\frac{1}{(\log x)^{2-2R-5}} \right) \right).$$

By making R going to infinity, the above equality together with (4.27) show that

$$(4.30) \quad B(x) \sim \frac{37}{16} \frac{Cx}{(\log x)^{\frac{1}{4}}}, \quad x \rightarrow \infty.$$

In a similar way, we can show that $\widehat{B}(x)$ defined in (4.17) satisfies

$$\widehat{B}(x) \sim \frac{1}{31} B(x) \sim \frac{37}{16 \cdot 31} \frac{x}{(\log x)^{\frac{1}{4}}}$$

which, with (4.16) and (4.15), completes the proof of Theorem 4.1 with

$$\kappa = \frac{37}{16} \left(1 + \frac{1}{31} \right) C = \frac{74}{31} C = 1.469696766\dots$$

□

Numerical computation of $A(x)$.

There are three ways to compute $A(x)$. The first one uses the definition of \mathcal{A} and simultaneously calculates the number of partitions $p(\mathcal{A}, n)$ for $n \leq x$; it is rather slow. The second one is based on the relation (1.10) and the congruences (2.19) and (2.23) satisfied by $\sigma(\mathcal{A}, n)$. The third one calculates $\omega_j(n)$, $0 \leq j \leq 5$, in view of applying Theorem 2.2. The two last methods can be encoded in a sieving process

The following table displays the values of $A(x)$, $A_1(x)$, ..., $A_4(x)$ as defined in (4.14) and also

$$c(x) = \frac{A(x)(\log x)^{\frac{1}{4}}}{x}, \quad c_1(x) = \frac{A_1(x)(\log x)^{\frac{1}{4}}}{x}.$$

It seems that $c(x)$ and $c_1(x)$ converge very slowly to $\kappa = 1.469696766\dots$, which is impossible to guess from the table.

x	$A(x)$	$c(x)$	$A_1(x)$	$c_1(x)$	$A_2(x)$	$A_3(x)$	$A_4(x)$
10^3	480	0.7782	20	0.032	44	233	183
10^4	4543	0.7914	361	0.063	532	2294	1356
10^5	43023	0.7925	5087	0.094	5361	21810	10765
10^6	411764	0.7939	60565	0.117	52344	208633	90222
10^7	3981774	0.7978	680728	0.136	506199	2007168	787679
10^8	38719773	0.8022	7403138	0.153	4887357	19390529	7038749

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