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Dominant residue classes concerning the summands of partitions

Cécile Dartyge (Nancy) and Mihály Szalay (Budapest) *

To Jean-Marc Deshouillers on his 60-th birthday

1. Introduction

Recently András Sárközy and the authors [3] proved that for almost all partitions of an integer n , the parts are well distributed in arithmetic progressions modulo d for $d < n^{1/2-\varepsilon}$. This range for d is large if we compare it with the largest parts of almost all partitions. Indeed, Erdős and Lehner [6] proved in 1941 that for almost all partitions of n (with at most $o(p(n))$ exceptions) the biggest part is $(1 + o(1))\frac{\sqrt{6n}}{2\pi} \log n$. However this well distribution is limited by some phenomenon of preponderance of parts with small module. For example, it is well known that for almost all partitions the number of parts equal to 1 is $\approx \sqrt{n}$ (see [11]).

In order to some applications, the aim of this paper is to study precisely the distribution of the parts congruent to j modulo d . Let $d \geq 2$ and $\mathcal{R} = \{N_1, \dots, N_d\}$ a set of some positive integers.

We denote by $\Pi_d(n, \mathcal{R})$ the number of partitions of n with exactly N_r parts congruent to $r \pmod d$ for $1 \leq r \leq d$.

We immediately remark that $\Pi_d(n, \mathcal{R}) \geq 1$ if and only if $n \equiv R \pmod d$ with

$$(1.1) \quad R := \sum_{r=1}^d r N_r.$$

It is the reason why we will compute $\Pi_d(n + R, \mathcal{R})$ for $n \equiv 0 \pmod d$. In the following result we give an asymptotic formula for $\Pi_d(n + R, \mathcal{R})$ in a large range of N_1, \dots, N_d .

Theorem 1.1. *Let $0 < \varepsilon < 10^{-2}$. There exists n_0 such that for $n \geq n_0$, $d \leq n^{\frac{1}{8}-\varepsilon}$, $d|n$ and*

$$(1.2) \quad \left(\frac{3}{4} + \varepsilon\right) \frac{\sqrt{6n}}{2\pi d} \log n \leq N_r \leq \frac{n^{\frac{5}{8}}}{d} \quad (1 \leq r \leq d)$$

we have

$$(1.3) \quad \begin{aligned} \Pi_d(n + R, \mathcal{R}) &= (1 + o(1)) p(n) d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}}\right)^{\frac{d-1}{2}} \\ &\times \exp\left(-\frac{\sqrt{6n}}{\pi d} \sum_{r=1}^d \exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right)\right). \end{aligned}$$

The condition $d \leq n^{\frac{1}{8}-\varepsilon}$ is a consequence of the use of saddle point method. This condition is probably not optimal. It is clear that we must have $d \ll \sqrt{n} \log n$ but

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perhaps another approach could give some significant result in some part of the range $[n^{\frac{1}{8}-\varepsilon}, n^{\frac{1}{2}-\varepsilon}]$.

The error term $(o(1))$ in (1.3) depends mainly on the computation of the term S_1 (see paragraphs 4 and 5). We could replace it by $O(n^{-\varepsilon/6})$. In fact if we take a smaller range for N_1, \dots, N_d than the one given in (1.2), then we can obtain a more precise error term in (1.3).

The first part of the paper (the paragraphs 2,3,4,5,6,7) is devoted to the proof of this theorem by the saddle point method.

In the second part of the paper we derive many results on the distributions of the parts in residue classes. Some of these results solve problems posed in [1], [2] and [4].

We first obtain a statistical result on the size of all N_r for $1 \leq r \leq d$.

Corollary 1.2. *For $0 < \varepsilon < 10^{-2}$, $n \geq n_2(\varepsilon)$, and $d \leq n^{\frac{1}{8}-\varepsilon}$, in almost all partitions of n the number of summands $\equiv r \pmod{d}$ are between $\lceil (\frac{3}{4} + \varepsilon) \frac{\sqrt{6}}{2\pi d^2} \sqrt{n \log n} \rceil d$ and $\lfloor \frac{\sqrt{6}n^{5/8}}{\pi d^2} \rfloor d - 1$ simultaneously for $r = 1, \dots, d$.*

It should be noted that, for $d = o(\log^2 n)$, Corollary 1.2 is implied by the Theorem 1 and Corollary 2 of the article of András Sárközy with the two authors [3]. Next we will state a corollary which shows that for almost all partitions, two given residue classes doesn't contain the same number of summands.

Corollary 1.3. *For $0 < \varepsilon < 10^{-2}$, $n \geq n_3(\varepsilon)$, $d \leq n^{\frac{1}{8}-\varepsilon}$, and $1 \leq a < b \leq d$, the number of partitions of n with the same number of summands in the residue classes a and $b \pmod{d}$ is $o(p(n))$.*

In [1] and [2] Dartyge and Sárközy proved that for a positive proportion of partitions some residue classes are much more represented than others. For a given partition Π of n and for any $1 \leq j \leq d$, we denote by $N_j = N_j(\Pi)$ the number of parts congruent to j modulo d . Dartyge and Sárközy [2] showed that, for d fixed, n large enough ($n \geq n_1(d)$) and any $1 \leq a < b \leq d$, the inequality $N_a - N_b > \frac{(a+b)\sqrt{n}}{50ab}$ is satisfied for at least $p(n)/12$ partitions of n . In the introduction of [1] and in the end of [4] it is conjectured that for $1 \leq a < b \leq d$ there exists $C = C(a, b, d) > 1/2$ such that $N_a > N_b$ for at least $Cp(n)$ partitions of n .

In the following theorem we prove this conjecture. In fact, we obtain an asymptotic estimation of the number of such partitions.

Theorem 1.4. *For any $0 < \varepsilon < 10^{-2}$, $n > n_4(\varepsilon)$, $d \leq n^{\frac{1}{8}-\varepsilon}$ and $1 \leq a < b \leq d$, we have the three following properties.*

(i) *The number of partitions of n in which there are more parts $\equiv a \pmod{d}$ than parts $\equiv b \pmod{d}$ is*

$$(1.4) \quad (1 + o(1))p(n) \frac{1}{\Gamma(\frac{a}{d})\Gamma(\frac{b}{d})} \int_0^\infty x^{\frac{a}{d}-1} e^{-x} \left(\int_x^\infty y^{\frac{b}{d}-1} e^{-y} dy \right) dx.$$

(ii) *The number of partitions of n in which there are at least as many parts $\equiv a \pmod{d}$ as parts $\equiv b \pmod{d}$ is*

$$(1.5) \quad (1 + o(1))p(n) \frac{1}{\Gamma(\frac{a}{d})\Gamma(\frac{b}{d})} \int_0^\infty x^{\frac{a}{d}-1} e^{-x} \left(\int_x^\infty y^{\frac{b}{d}-1} e^{-y} dy \right) dx.$$

(iii) *For fixed d , $1 \leq a < b \leq d$, and large enough n , the number of partitions of n in which there are more parts $\equiv a \pmod{d}$ than parts $\equiv b \pmod{d}$ is*

$$(1.6) \quad > p(n) \left(\frac{1}{2} + \frac{b-a}{12d} \right) \geq p(n) \left(\frac{1}{2} + \frac{1}{12d} \right).$$

On the other hand, this number is less than

$$(1.7) \quad p(n)2^{-\frac{a}{d}}(1 + o(1)).$$

When $b = d$ in the above theorem, it is possible to compute the integrals in (1.4) or in (1.5). We obtain that for $1 \leq a < d$, the number of partitions of n such that $N_a > N_d$ (or such that $N_a \geq N_d$) is $(1 + o(1))2^{-a/d}p(n)$.

In [2], Dartyge and Sárközy proved by combinatorics arguments that for at least $p(n)/d$ partitions of n , we have $N_1 \geq N_j$ for any $2 \leq j \leq d$. In [4], it is conjectured that there are at least $(\frac{1}{d} + c)p(n)$ such partitions for some $c = c(d) > 0$. We state this for fixed d in the following theorem.

Theorem 1.5. *For fixed $d \geq 2$ and $1 \leq a \leq d$, the three following assertions are satisfied.*

(i) *The number of partitions of n in which there are more parts $\equiv a \pmod{d}$ than parts $\equiv b \pmod{d}$ for all $b \in \{1, \dots, d\} \setminus \{a\}$ is*

$$(1 + o(1))p(n) \frac{1}{\Gamma\left(\frac{1}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)} \int_0^\infty x^{\frac{a}{d}-1} e^{-x} \left(\prod_{\substack{r=1 \\ r \neq a}}^d \int_x^\infty y^{\frac{r}{d}-1} e^{-y} dy \right) dx.$$

(ii) *The number of partitions of n in which there are at least as many parts $\equiv a \pmod{d}$ as parts $\equiv b \pmod{d}$ for all $b \in \{1, \dots, d\} \setminus \{a\}$ is*

$$(1 + o(1))p(n) \frac{1}{\Gamma\left(\frac{1}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)} \int_0^\infty x^{\frac{a}{d}-1} e^{-x} \left(\prod_{\substack{r=1 \\ r \neq a}}^d \int_x^\infty y^{\frac{r}{d}-1} e^{-y} dy \right) dx.$$

(iii) *For n large enough, the number of partitions of n in which there are more parts $\equiv 1 \pmod{d}$ than parts $\equiv b \pmod{d}$ for all $b \in \{2, \dots, d\}$ is*

$$> p(n) \left(\frac{1}{d} + \frac{1}{14d} \left(1 - \frac{1}{d} \right) \right).$$

In [2], Dartyge and Sárközy proved that for at least $\frac{p(n)}{d!}(1 + O(d!d^4/\sqrt{n}))$ we have $N_1 > N_2 > \dots > N_d$. In [4] we conjectured that this holds in fact for at least $Cp(n)$ partitions with $C > 1/d!$. In the following result we solve this conjecture for fixed d .

Theorem 1.6. *For fixed $d \geq 2$, the number of partitions of n in which there are more parts $\equiv a \pmod{d}$ than parts $\equiv b \pmod{d}$ for any $1 \leq a < b \leq d$ is*

$$\frac{(1 + o(1))p(n)}{\Gamma\left(\frac{1}{d}\right)\Gamma\left(\frac{2}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)} \int_0^\infty x_1^{\frac{1}{d}-1} e^{-x_1} \int_{x_1}^\infty x_2^{\frac{2}{d}-1} e^{-x_2} \int_{x_2}^\infty x_3^{\frac{3}{d}-1} e^{-x_3} \cdots \int_{x_{d-1}}^\infty x_d^{\frac{d}{d}-1} e^{-x_d} dx_d \cdots dx_1.$$

For n large enough this is

$$> \frac{p(n)}{d!}.$$

We won't give the details of the proof of this theorem because it is an adaptation of the proof of Theorem 1.5. In fact, the proof of Theorem 1.5 may be also adapted easily to obtain the more general result :

Theorem 1.7. *For fixed $d \geq 2$ and any permutation σ on the set $\{1, \dots, d\}$, the number of partitions of n in which there are more parts $\equiv \sigma(a) \pmod{d}$ than parts $\equiv \sigma(b) \pmod{d}$ for any $1 \leq a < b \leq d$ is*

$$\frac{(1 + o(1))p(n)}{\Gamma\left(\frac{1}{d}\right)\Gamma\left(\frac{2}{d}\right)\cdots\Gamma\left(\frac{d}{d}\right)} \int_0^\infty x_1^{\frac{\sigma(1)}{d}-1} e^{-x_1} \int_{x_1}^\infty x_2^{\frac{\sigma(2)}{d}-1} e^{-x_2} \int_{x_2}^\infty x_3^{\frac{\sigma(3)}{d}-1} e^{-x_3} \cdots \int_{x_{d-1}}^\infty x_d^{\frac{\sigma(d)}{d}-1} e^{-x_d} \prod_{r=1}^d dx_r.$$

With much more computations some results could be more precise. Some estimations are obtained only for d fixed mainly because in some steps we apply many times Corollary 1.3. It is probably possible to improve this corollary by a more direct use of the saddle point method.

2. A lemma on some generating function

In order to use the saddle point method we define the generating function :

$$G(z) := \sum_{\substack{n=0 \\ n \equiv R \pmod{d}}}^{\infty} \Pi_d(n, \mathcal{R}) z^n.$$

We will prove that this function is a finite product.

Lemma 2.1. *For $z \in \mathbb{C}$ and $|z| < 1$, we have*

$$G(z) = \frac{z^{1N_1 + \dots + dN_d}}{\prod_{r=1}^d \prod_{j=1}^{N_r} (1 - z^{jd})}.$$

We will give two proofs of this result. The first one uses a multi-variable generating function and a formula of Euler, the second is more combinatoric.

First proof of Lemma 2.1. According to Euler's theorem, for $|t| < 1$ and $|q| < 1$, we have

$$(2.1) \quad 1 + \sum_{n=1}^{\infty} \frac{t^n}{(1-q)(1-q^2)\cdots(1-q^n)} = \prod_{n=0}^{\infty} \frac{1}{1-tq^n},$$

for example, see [10] Theorem 349 p. 280.

For $z, w_r \in \mathbb{C}$, $|z| < 1$, and $|w_r| < |z|^{-r}$, ($1 \leq r \leq d$) we have

$$(2.2) \quad \prod_{r=1}^d \prod_{k_r=0}^{\infty} \frac{1}{1 - w_r z^{r+k_r d}} = \prod_{r=1}^d \prod_{k_r=0}^{\infty} (1 + w_r z^{r+k_r d} + w_r^2 z^{2(r+k_r d)} + \dots) \\ = \sum_{N_1=1}^{\infty} \cdots \sum_{N_d=1}^{\infty} \left(\sum_{n \in \mathbb{N}}^* \Pi_d(n, \{N_1, \dots, N_d\}) z^n \right) w_1^{N_1} \cdots w_d^{N_d},$$

where $*$ indicates that the sum is over the $n \in \mathbb{N}$ such that $n \equiv R \pmod{d}$.

On the other hand, for $1 \leq r \leq d$, we write $w_r z^{r+k_r d} = (w_r z^r)(z^d)^{k_r}$ and we apply (2.1) with $t = w_r z^r$, $q = z^d$:

$$(2.3) \quad \prod_{r=1}^d \prod_{k_r=0}^{\infty} \frac{1}{1 - w_r z^{r+k_r d}} = \prod_{r=1}^d \left(1 + \sum_{N_r=1}^{\infty} \frac{(w_r z^r)^{N_r}}{(1-z^d)(1-z^{2d})\cdots(1-z^{N_r d})} \right) \\ = \prod_{r=1}^d \sum_{N_r=0}^{\infty} \frac{w_r^{N_r} z^{r N_r}}{\prod_{j=1}^{N_r} (1 - z^{jd})} \\ = \sum_{N_1=0}^{\infty} \cdots \sum_{N_d=0}^{\infty} \left(\frac{z^{N_1 + \dots + dN_d}}{\prod_{r=1}^d \prod_{j=1}^{N_r} (1 - z^{jd})} \right) w_1^{N_1} \cdots w_d^{N_d}.$$

We finish the proof by comparing the coefficient of $w_1^{N_1} \cdots w_r^{N_r}$ in (2.2) and (2.3).

Second proof of Lemma 2.1. Let Π be a partition of n counted in $\Pi(n, \mathcal{R})$. This partition is of the form :

$$\Pi : n = \sum_{r=1}^d \sum_{j=1}^{N_r} (r + \lambda_{r,j} d),$$

with

$$\lambda_{r,1} \geq \dots \geq \lambda_{r,N_r} \geq 0 \quad (1 \leq r \leq d).$$

Thus we have

$$n = R + d \sum_{r=1}^d m_r, \quad \text{with } m_r = \sum_{j=1}^{N_r} \lambda_{r,j} \quad (1 \leq r \leq d).$$

For each $1 \leq r \leq d$, $\lambda_{r,1}, \dots, \lambda_{r,N_r}$ is a partition of m_r in at most N_r parts. Let $p_{N_r}(m_r)$ denote the number of such partitions. We have

$$\begin{aligned} G(z) &= z^R \sum_{\substack{n=0 \\ n \equiv R \pmod{d}}}^{\infty} \sum_{\substack{m_1 + \dots + m_d = \frac{n-R}{d} \\ m_j \in \mathbb{N}}} p_{N_1}(m_1) \cdots p_{N_d}(m_d) z^{d(m_1 + \dots + m_d)} \\ &= z^R \prod_{r=1}^d \left(\sum_{m=0}^{\infty} z^{dm} p_{N_r}(m) \right) \\ &= \frac{z^R}{\prod_{r=1}^d \prod_{j=1}^{N_r} (1 - z^{dj})}, \end{aligned}$$

where we have used the formula for $|x| < 1$

$$\sum_{n=0}^{\infty} p_m(n) x^n = \frac{1}{\prod_{j=1}^m (1 - x^j)}.$$

3. The saddle point method

For $v \in \mathbb{C}$, $|v| < 1$, it follows from Lemma 2.1 that

$$\sum_{m=0}^{\infty} \Pi_d(dm + R, \mathcal{R}) v^{dm} = \prod_{r=1}^d \prod_{j=1}^{N_r} (1 - v^{jd})^{-1}.$$

For $d|n$, and some $0 < \varrho < 1$, we obtain by the Cauchy formula that

$$\Pi_d(n + R, \mathcal{R}) = \frac{1}{2i\pi} \int_{|v|=\varrho} v^{-n-1} \prod_{r=1}^d \prod_{j=1}^{N_r} (1 - v^{jd})^{-1} dv.$$

Let $x > 0$, $\varrho = e^{-x}$, $z = x + iy$, $v = e^{-z}$. Then we have :

$$\begin{aligned} \Pi_d(n + R, \mathcal{R}) &= \frac{1}{2\pi} \int_{-\pi}^{\pi} \left\{ \prod_{r=1}^d \prod_{j=1}^{N_r} \frac{1}{1 - \exp(-jd(x + iy))} \right\} \exp(n(x + iy)) dy \\ &= \frac{d}{2\pi} \int_{-\pi/d}^{\pi/d} \left\{ \prod_{r=1}^d \prod_{j=1}^{N_r} \frac{1}{1 - \exp(-jd(x + iy))} \right\} \exp(n(x + iy)) dy \end{aligned}$$

since the integrand is periodic in y and has period $2\pi/d$. For $\Re w > 0$, we set

$$f(w) := \prod_{\nu=1}^{\infty} (1 - \exp(-\nu w))^{-1}$$

and

$$g_k(w) := \prod_{\nu=1}^k (1 - \exp(-\nu w))^{-1} = f(w) \prod_{\nu=k+1}^{\infty} (1 - \exp(-\nu w)).$$

With this notation,

$$\Pi_d(n + R, \mathcal{R}) = \frac{d}{2\pi} \int_{-\pi/d}^{\pi/d} \left\{ \prod_{r=1}^d g_{N_r}(d(x + iy)) \right\} \exp(n(x + iy)) dy.$$

For $\varepsilon > 0$, $0 < \varepsilon < 10^{-2}$, $d \leq n^{\frac{1}{8}-\varepsilon}$ and $n > n_0$, we consider the interval

$$I = I_{n,d,\varepsilon} := \left[\left(\frac{3}{4} + \varepsilon \right) \frac{\sqrt{6}}{2\pi d} \sqrt{n} \log n, \frac{n^{\frac{5}{8}}}{d} \right].$$

We will estimate $\Pi_d(n + R, \mathcal{R})$ for $N_1, \dots, N_d \in I$ and $d|n$. Choosing $x = x_0 = \frac{\pi}{\sqrt{6n}}$, $y_1 = n^{-\frac{3}{4}+\frac{\varepsilon}{3}}$, $y_2 = n^{-\frac{5}{8}+\frac{\varepsilon}{3}}$ and $y_3 = \pi x_0$, we write $\Pi_d(n + R, \mathcal{R})$ as

$$(3.1) \quad \begin{aligned} \Pi_d(n + R, \mathcal{R}) &= \frac{d}{2\pi} \left\{ \int_{|y| \leq y_1} + \int_{y_1 \leq |y| \leq y_2} + \int_{y_2 \leq |y| \leq y_3} + \int_{y_3 \leq |y| \leq \pi/d} \right\} \\ &= S_1 + S_2 + S_3 + S_4. \end{aligned}$$

Theorem 1.1 will be derived by the following lemma :

Lemma 3.1. *Under the hypotheses of Theorem 1.1, we have*

$$(3.2) \quad S_1 = (1 + o(1)) p(n) d^{\frac{2+d}{2}} \left(\frac{x_0}{2\pi} \right)^{\frac{d-1}{2}} \exp \left(- \frac{1}{dx_0} \sum_{r=1}^d \exp(-dN_r x_0) \right);$$

$$(3.3) \quad S_i = o(S_1) \quad (i = 2, 3, 4).$$

In the next paragraph we state some estimates of g_k and in the paragraphs 5, 6, and 7 we prove (3.2), (3.3) respectively.

4. The function g_k

By elementary arguments we will prove the following lemma which compares g_k with f .

Lemma 4.1. (i) *For $k \in I$ and $|y| \leq \pi/d$ we have*

$$(4.1) \quad \begin{aligned} g_k(d(x_0 + iy)) &= f(d(x_0 + iy)) \exp \left\{ - \frac{\exp(-dk(x_0 + iy))}{d(x_0 + iy)} \right\} \\ &\times \exp \left\{ O(\exp(-dkx_0)) + O\left(\sqrt{\frac{n}{d}} \exp(-2dkx_0)\right) \right\}, \end{aligned}$$

and

$$(4.2) \quad g_k(d(x_0 + iy)) = f(d(x_0 + iy)) \exp\left(-\frac{\exp(-dkx_0)}{dx_0}\right) \\ \times \exp\left\{O(1) \exp(-dkx_0)(\sqrt{n}k|y| + 1 + \frac{\sqrt{n}}{d} \exp(-dkx_0))\right\}.$$

(ii) For $k \in I$ and $|y| \leq y_1$ we have

$$(4.3) \quad g_k(d(x_0 + iy)) = f(d(x_0 + iy)) \exp\left(-\frac{\exp(-dkx_0)}{dx_0}\right) \exp\left(O\left(\frac{n^{\frac{3}{8} + \frac{\epsilon}{8}}}{d} \exp(-dkx_0)\right)\right) \\ = (1 + o(d^{-1}))f(d(x_0 + iy)) \exp\left(-\frac{1}{dx_0} \exp(-dkx_0)\right).$$

Proof. Consider $g_k(dz)$ for $k \in I$ and $|y| \leq \pi/d$. If $\nu \geq k + 1$ then

$$|\exp(-\nu d(x_0 + iy))| = \exp(-\nu dx_0) < \exp(-kdx_0) \leq n^{-\frac{3}{8} - \frac{\epsilon}{2}}.$$

Therefore (here \log denotes the principal determination of logarithm defined on $\mathbb{C} \setminus \mathbb{R}^-$),

$$g_k(d(x_0 + iy)) = f(d(x_0 + iy)) \exp\left\{\sum_{\nu=k+1}^{\infty} \log(1 - \exp(-\nu d(x_0 + iy)))\right\} \\ = f(d(x_0 + iy)) \exp\left\{-\sum_{\nu=k+1}^{\infty} (\exp(-\nu d(x_0 + iy)) + O(\exp(-2\nu dx_0)))\right\} \\ = f(d(x_0 + iy)) \exp\left\{-\frac{\exp(-dk(x_0 + iy))}{\exp(d(x_0 + iy)) - 1} + O\left(\frac{\exp(-2dkx_0)}{\exp(2dx_0) - 1}\right)\right\}.$$

Here, $|d(x_0 + iy)| \leq dx_0 + \pi < 6$. Thus

$$\frac{1}{\exp(d(x_0 + iy)) - 1} = \frac{1}{d(x_0 + iy)} + O(1).$$

This yields that

$$g_k(d(x_0 + iy)) = f(d(x_0 + iy)) \\ \times \exp\left\{-\frac{\exp(-dk(x_0 + iy))}{d(x_0 + iy)} + O(\exp(-dkx_0)) + O\left(\frac{\sqrt{n}}{d} \exp(-2dkx_0)\right)\right\},$$

this ends the proof of (4.1).

To prove (4.2) we remark that

$$(4.4) \quad \left|\frac{\exp(-dk(x_0 + iy))}{d(x_0 + iy)} - \frac{\exp(-dkx_0)}{dx_0}\right| = \frac{\exp(-dkx_0)}{d} \left|\frac{\exp(-dkiy) - 1 - iyx_0^{-1}}{x_0 + iy}\right| \\ \leq \frac{\exp(-dkx_0)}{d} \frac{(dk|y| + |y|x_0^{-1})}{x_0} \\ = O(\sqrt{n}k|y| \exp(-dkx_0)),$$

since $x_0^{-1} = O(dk)$. It remains to insert (4.4) in (4.1) to obtain (4.2).

Now we prove (4.3). For $k \in I$ and $|y| \leq y_1 = n^{-\frac{3}{4}+\varepsilon}$, the different factors in the error term of (4.2) become :

$$\sqrt{n}k|y| + 1 + \frac{\sqrt{n}}{d} \exp(-dkx_0) \leq \sqrt{n} \frac{n^{5/8}}{d} n^{-\frac{3}{4}+\frac{\varepsilon}{3}} + \frac{d}{d} + \frac{\sqrt{n}}{d} n^{-\frac{3}{8}-\frac{\varepsilon}{2}} = O\left(\frac{n^{\frac{3}{8}+\frac{\varepsilon}{3}}}{d}\right),$$

and

$$(4.5) \quad \frac{n^{\frac{3}{8}+\frac{\varepsilon}{3}}}{d} \exp(-dkx_0) \leq \frac{n^{-\frac{\varepsilon}{6}}}{d} = o\left(\frac{1}{d}\right).$$

Consequently, for $k \in I$ and $|y| \leq y_1$,

$$\begin{aligned} g_k(d(x_0 + iy)) &= f(d(x_0 + iy)) \exp \left\{ -\frac{\exp(-dkx_0)}{dx_0} + O\left(\frac{n^{\frac{3}{8}+\frac{\varepsilon}{3}}}{d} \exp(-dkx_0)\right) \right\} \\ &= (1 + o(d^{-1})) f(d(x_0 + iy)) \exp \left\{ -\frac{\exp(-dkx_0)}{dx_0} \right\}, \end{aligned}$$

this ends the proof of (4.3).

5. The main term S_1

By (3.1) and Lemma 4.1 we have

$$\begin{aligned} S_1 &= \frac{d}{2\pi} \int_{-y_1}^{y_1} \left\{ \prod_{r=1}^d g_{N_r}(d(x_0 + iy)) \right\} \exp(n(x_0 + iy)) dy \\ &= \frac{d}{2\pi} \exp \left(-\frac{1}{dx_0} \sum_{r=1}^d \exp(-dN_r x_0) \right) \\ &\quad \times \int_{-y_1}^{y_1} f^d(d(x_0 + iy)) \exp \left\{ n(x_0 + iy) + O\left(\frac{n^{\frac{3}{8}+\frac{\varepsilon}{3}}}{d} \sum_{r=1}^d \exp(-dN_r x_0)\right) \right\} dy \\ &= d \exp \left(-\frac{1}{dx_0} \sum_{r=1}^d \exp(-dN_r x_0) \right) \\ &\quad \times \frac{1}{2\pi} \int_{-y_1}^{y_1} f^d(d(x_0 + iy)) \exp \left(n(x_0 + iy) + O(n^{-\frac{\varepsilon}{6}}) \right) dy. \end{aligned}$$

Next we use the well-known formula (see for example [7] or [8])

$$f(w) = \exp \left(\frac{\pi^2}{6w} + \frac{1}{2} \log \frac{w}{2\pi} + O(|w|) \right)$$

for $w \rightarrow 0$ in $|\arg w| \leq \kappa < \pi/2$ and $\Re w > 0$.

For $|y| \leq y_3 = \pi x_0$,

$$\begin{aligned} f(d(x_0 + iy)) &= \exp \left(\frac{\pi^2}{6d(x_0 + iy)} + \frac{1}{2} \log \left(\frac{d(x_0 + iy)}{2\pi} \right) + O(dx_0) \right), \\ f^d(d(x_0 + iy)) &= \exp \left(\frac{\pi^2}{6(x_0 + iy)} + \frac{d}{2} \log \left(\frac{d(x_0 + iy)}{2\pi} \right) + O(d^2 x_0) \right) \\ &= f(x_0 + iy) \exp \left(\frac{d}{2} \log d + \frac{d-1}{2} \log \frac{x_0 + iy}{2\pi} + O(d^2 x_0) \right). \end{aligned}$$

For $|y| \leq y_2 = n^{-\frac{5}{8} + \frac{\epsilon}{3}}$,

$$(5.1) \quad \begin{aligned} f^d(d(x_0 + iy)) &= f(x_0 + iy) \exp\left(\frac{d}{2} \log d + \frac{d-1}{2} \log \frac{x_0}{2\pi} + O(d)\left(\frac{|y|}{x_0} + dx_0\right)\right) \\ &= f(x_0 + iy) d^{d/2} \left(\frac{x_0}{2\pi}\right)^{\frac{d-1}{2}} \exp(O(dn^{-\frac{1}{8} + \frac{\epsilon}{3}})). \end{aligned}$$

Finally by (5.1) and (4.5),

$$\begin{aligned} S_1 &= d^{1+\frac{d}{2}} \left(\frac{x_0}{2\pi}\right)^{\frac{d-1}{2}} \exp\left(-\frac{1}{dx_0} \sum_{r=1}^d \exp(-dN_r x_0)\right) \\ &\quad \times \left\{ \frac{1}{2\pi} \int_{-y_1}^{y_1} f(x_0 + iy) \exp(n(x_0 + iy)) dy \right. \\ &\quad \left. + o(1) \int_{-y_1}^{y_1} |f(x_0 + iy) \exp(n(x_0 + iy))| dy \right\}. \end{aligned}$$

For $|y| \leq y_1$, --- as it is well known ---

$$\begin{aligned} f(x_0 + iy) \exp(n(x_0 + iy)) &= \exp\left(\frac{\pi^2}{6(x_0 + iy)} + \frac{1}{2} \log\left(\frac{x_0 + iy}{2\pi}\right) + o(1) + nx_0 + iny\right) \\ &= \exp\left(\frac{\pi^2}{6x_0} \left(1 - \frac{iy}{x_0} - \frac{y^2}{x_0^2} + O\left(\frac{y_1^3}{x_0^3}\right)\right)\right) \\ &\quad + \frac{1}{2} \log\left(\frac{x_0}{2\pi}\right) + O\left(\frac{y_1}{x_0}\right) + o(1) + nx_0 + iny \\ &= \exp\left(\frac{\pi^2}{6x_0} - \frac{\pi^2 y^2}{6x_0^3} + \frac{1}{2} \log\left(\frac{x_0}{2\pi}\right) + o(1) + nx_0\right) \\ &= (1 + o(1)) |f(x_0 + iy) \exp(n(x_0 + iy))|, \end{aligned}$$

and

$$\frac{1}{2\pi} \int_{-y_1}^{y_1} f(x_0 + iy) \exp(n(x_0 + iy)) dy = (1 - o(1)) p(n).$$

This ends the proof of (3.2).

6. The term S_2

We write

$$S_2 = \int_{y_1}^{y_2} + \int_{-y_2}^{-y_1} = S_2^+ + S_2^-.$$

Thus we have

$$S_2^+ = \frac{d}{2\pi} \int_{y_1}^{y_2} \left\{ \prod_{r=1}^d g_{N_r}(d(x_0 + iy)) \right\} \exp(n(x_0 + iy)) dy.$$

From Lemma 4.1 we have for $k \in I$ and $|y| \leq \pi/d$

$$\begin{aligned} |g_k(d(x_0 + iy))| &= |f(d(x_0 + iy))| \exp\left\{-\Re \frac{\exp(-dk(x_0 + iy))}{d(x_0 + iy)}\right. \\ &\quad \left.+ O(\exp(-dkx_0)) + O\left(\frac{\sqrt{n}}{d} \exp(-2dkx_0)\right)\right\}. \end{aligned}$$

If $k \in I$ and $y_1 \leq y \leq y_2 = n^{-\frac{5}{8} + \frac{\varepsilon}{3}}$ then

$$\begin{aligned}
& |g_k(d(x_0 + iy))| = |f(d(x_0 + iy))| \exp \left\{ - \frac{\exp(-dkx_0)}{dx_0} \Re \frac{\exp(-dkiy)}{1 + i \frac{y}{x_0}} \right. \\
& \quad \left. + O(n^{-\frac{3}{8} - \frac{\varepsilon}{2}}) + O\left(\frac{n^{-\frac{1}{4} - \varepsilon}}{d}\right) \right\} \\
(6.1) \quad & = |f(d(x_0 + iy))| \exp \left\{ - \frac{\exp(-dkx_0)}{dx_0} \Re(\exp(-dkiy)(1 + O(\frac{y_2}{x_0}))) + o(d^{-1}) \right\} \\
& = |f(d(x_0 + iy))| \exp \left\{ - \frac{\exp(-dkx_0)}{dx_0} (\cos(dky) + O(n^{-\frac{1}{8} + \frac{\varepsilon}{3}})) + o(d^{-1}) \right\} \\
& = |f(d(x_0 + iy))| \exp \left\{ - \frac{\exp(-dkx_0)}{dx_0} \left(1 - 2 \sin^2\left(\frac{dky}{2}\right)\right) + o(d^{-1}) \right\}.
\end{aligned}$$

If $k \leq \frac{\sqrt{6}}{\pi d} \sqrt{n} \log n$ then

$$\begin{aligned}
(6.2) \quad & \frac{\exp(-dkx_0)}{dx_0} 2 \sin^2\left(\frac{dky}{2}\right) = O\left(\frac{\sqrt{n}}{d}\right) (dky_2)^2 \exp(-dkx_0) \\
& = O\left(\frac{\sqrt{n}}{d}\right) n^{-\frac{3}{8} - \frac{\varepsilon}{2}} (\log^2 n) n^{-\frac{1}{4} + \frac{2\varepsilon}{3}} = o(d^{-1}).
\end{aligned}$$

If $k \geq \frac{\sqrt{6n}}{\pi d} \log n$ then

$$(6.3) \quad \frac{\exp(-dkx_0)}{dx_0} 2 \sin^2\left(\frac{dky}{2}\right) = O\left(\frac{\sqrt{n}}{d}\right) \exp(-dkx_0) = O\left(\frac{\sqrt{n}}{d}\right) n^{-1} = o(d^{-1}).$$

By (6.1), (6.2), (6.3), and (5.1) we have

$$\begin{aligned}
|S_2^+| & \leq \frac{d}{2\pi} \exp\left(-\sum_{r=1}^d \frac{\exp(-dN_r x_0)}{dx_0}\right) \int_{y_1}^{y_2} |f^d(d(x_0 + iy))| \exp(nx_0 + o(1)) dy \\
& = O(d) \exp\left(-\sum_{r=1}^d \frac{\exp(-dN_r x_0)}{dx_0}\right) d^{\frac{d}{2}} \left(\frac{x_0}{2\pi}\right)^{\frac{d-1}{2}} \int_{y_1}^{y_2} |f(x_0 + iy)| \exp(nx_0) dy.
\end{aligned}$$

Here the usual estimation :

$$\begin{aligned}
|f(x_0 + iy)| & = \exp \left\{ \Re \frac{\pi^2}{6(x_0 + iy)} + O(\log n) \right\} \\
& \leq \exp \left\{ \frac{\pi^2}{6x_0} \cdot \frac{x_0^2}{x_0^2 + y_1^2} + O(\log n) \right\}
\end{aligned}$$

yields that $S_2^+ = o(S_1)$ and the same goes for S_2^- .

7. The terms S_3 and S_4

Like in the previous paragraph we write

$$S_3 = \int_{y_2 \leq y \leq y_3} + \int_{-y_3 \leq y \leq -y_2} = S_3^+ + S_3^-$$

and in the same way we write $S_4 = S_4^+ + S_4^-$. Similarly, for $y_2 \leq |y| \leq y_3 = \pi x_0$,

$$|f^d(d(x_0 + iy))| = |f(x_0 + iy)| d^{\frac{d}{2}} \left(\frac{x_0}{2\pi}\right)^{\frac{d-1}{2}} \exp(O(d \log n))$$

and

$$\begin{aligned} |g_k(d(x_0 + iy))| &= |f(d(x_0 + iy))| \exp \left\{ -\Re \frac{\exp(-dk(x_0 + iy))}{d(x_0 + iy)} + o(d^{-1}) \right\} \\ &\leq |f(d(x_0 + iy))| \exp \left\{ + \frac{\exp(-dkx_0)}{dx_0} + o(d^{-1}) \right\} \\ &\leq |f(d(x_0 + iy))| \exp \left\{ - \frac{\exp(-dkx_0)}{dx_0} + O\left(\frac{n^{\frac{1}{8} - \frac{\varepsilon}{2}}}{d}\right) \right\} \end{aligned}$$

yield that $|S_3| = o(S_1)$ since

$$\frac{\pi^2}{6x_0} \cdot \frac{x_0^2}{x_0^2 + y_2^2} \leq \frac{\pi^2}{6x_0} \left(1 - \frac{y_2^2}{2x_0^2}\right) \leq \frac{\pi^2}{6x_0} - n^{\frac{1}{4}}.$$

Finally, for $y_3 \leq |y| \leq \pi/d$, we obtain again that

$$|g_k(d(x_0 + iy))| \leq |f(d(x_0 + iy))| \exp \left\{ - \frac{\exp(-dkx_0)}{dx_0} + O\left(\frac{n^{\frac{1}{8} - \frac{\varepsilon}{2}}}{d}\right) \right\}.$$

Since

$$f(w) = \exp \left(\sum_{m=1}^{\infty} \frac{1}{m(\exp(mw) - 1)} \right)$$

for $\Re w > 0$, we have

$$\begin{aligned} |f(w)| &\leq \exp \left(\Re \frac{1}{e^w - 1} + \sum_{m=2}^{\infty} \frac{1}{m|e^{mw} - 1|} \right) \\ &\leq \exp \left(\frac{1}{|e^w - 1|} + \frac{1}{\Re w} \left(\frac{\pi^2}{6} - 1\right) \right) \\ &\leq \exp \left(\frac{1}{\frac{2}{\pi} |\Im w|} + \frac{1}{\Re w} \left(\frac{\pi^2}{6} - 1\right) \right) \end{aligned}$$

if $|\Im w| \leq \pi$. Thus

$$\begin{aligned} |f(d(x_0 + iy))| &\leq \exp \left(\frac{\pi}{2d|y|} + \frac{1}{dx_0} \left(\frac{\pi^2}{6} - 1\right) \right), \\ |f^d(d(x_0 + iy))| &\leq \exp \left(\frac{\pi}{2|y|} + \frac{1}{x_0} \left(\frac{\pi^2}{6} - 1\right) \right) \leq \exp \left(\frac{\pi^2}{6x_0} - \frac{1}{2x_0} \right). \end{aligned}$$

Observing that

$$d^{-\frac{d}{2}} \left(\frac{2\pi}{x_0}\right)^{\frac{d-1}{2}} = \exp(O(d \log n))$$

we see that $S_4 = o(S_1)$, this ends the proof of Lemma 3.1 and Theorem 1.1 is proved.

8. When $n \equiv R \pmod{d}$

We are going to apply Theorem 1.1 for $n - R$ instead of n when $n \equiv R \pmod{d}$. In this section we will derive from Theorem 1.1 the following result :

Corollary 8.1. For $0 < \varepsilon < 10^{-2}$, $n \geq n_1$, $d \leq (n - n^{3/4})^{\frac{1}{8} - \varepsilon}$, $n \equiv R \pmod{d}$, and

$$(8.1) \quad \left(\frac{3}{4} + \varepsilon\right) \frac{\sqrt{6n}}{2\pi d} \log n \leq N_r \leq \frac{\sqrt{6} n^{5/8}}{\pi d} \quad (r = 1, \dots, d)$$

we have

$$\Pi_d(n, \mathcal{R}) = (1 + o(1))p(n)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}}\right)^{\frac{d-1}{2}} \exp\left\{-\frac{\pi R}{\sqrt{6n}} - \frac{\sqrt{6n}}{\pi d} \sum_{r=1}^d \exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right)\right\}.$$

Proof. Under the hypotheses of Corollary 8.1, we have

$$R < \frac{n^{\frac{5}{8}}}{d} \cdot \frac{d(d+1)}{2} \leq dn^{\frac{5}{8}} < n^{\frac{3}{4} - \varepsilon} < n^{\frac{3}{4}},$$

thus $n - R > n - n^{3/4}$, $\frac{\sqrt{6}}{\pi} n^{5/8} < (n - R)^{5/8}$, and

$$\begin{aligned} n - R &= n(1 + O(n^{-1/4})) = n \exp(O(n^{-1/4})) \\ \sqrt{n - R} &= \sqrt{n} \exp(O(n^{-1/4})) = \sqrt{n} + O(n^{1/4}) \\ \frac{1}{\sqrt{n - R}} &= \frac{1}{\sqrt{n}} \exp(O(n^{-1/4})) = \frac{1}{\sqrt{n}} + O(n^{-3/4}) \\ \left(\frac{1}{\sqrt{n - R}}\right)^{\frac{d-1}{2}} &= \left(\frac{1}{\sqrt{n}}\right)^{\frac{d-1}{2}} \exp(O(dn^{-1/4})) = \left(\frac{1}{\sqrt{n}}\right)^{\frac{d-1}{2}} (1 + o(1)). \end{aligned}$$

Next we compute the argument of the exponential in Theorem 1.1 :

$$\begin{aligned} \left(\frac{\sqrt{6n}}{\pi d} - \frac{\sqrt{6(n-R)}}{\pi d}\right) \sum_{r=1}^d \exp\left(-\frac{dN_r\pi}{\sqrt{6(n-R)}}\right) &= O\left(\frac{n^{1/4}}{d}\right) \sum_{r=1}^d \exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right) \\ &= O\left(\frac{n^{1/4}}{d}\right) dn^{-\frac{3}{8} - \frac{\varepsilon}{2}} \\ &= O(n^{-\frac{1}{8} - \frac{\varepsilon}{2}}) = o(1). \end{aligned}$$

In the same way we have for $1 \leq r \leq d$:

$$\begin{aligned} \exp\left(-\frac{dN_r\pi}{\sqrt{6(n-R)}}\right) &= \exp\left(-dN_r\pi\left(\frac{1}{\sqrt{6n}} + O(n^{-3/4})\right)\right) \\ &= \exp\left(-\frac{dN_r\pi}{\sqrt{6n}} + O\left(d\frac{n^{5/8}}{d}n^{-3/4}\right)\right) \\ &= (1 + O(n^{-1/8})) \exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right). \end{aligned}$$

It remains to sum this equality over $1 \leq r \leq d$:

$$\begin{aligned} \frac{\sqrt{6n}}{\pi d} \sum_{r=1}^d \exp\left(-\frac{dN_r\pi}{\sqrt{6(n-R)}}\right) &= \frac{\sqrt{6n}}{\pi d} (1 + O(n^{-1/8})) \sum_{r=1}^d \exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right) \\ &= \frac{\sqrt{6n}}{\pi d} \sum_{r=1}^d \exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right) + O\left(\frac{n^{\frac{1}{2} - \frac{1}{8}}}{d} dn^{-\frac{3}{8} - \frac{\varepsilon}{2}}\right) \\ &= \frac{\sqrt{6n}}{\pi d} \sum_{r=1}^d \exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right) + o(1). \end{aligned}$$

We apply Theorem 1.1:

$$(8.2) \quad \Pi_d(n, \mathcal{R}) = (1 + o(1))p(n - R)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}} \right)^{\frac{d-1}{2}} \exp \left(- \frac{\sqrt{6n}}{\pi d} \sum_{r=1}^d \exp \left(- \frac{dN_r \pi}{\sqrt{6n}} \right) \right).$$

From the asymptotic formula

$$p(n) = (1 + o(1)) \frac{1}{4n\sqrt{3}} \exp \left(\frac{2\pi\sqrt{n}}{\sqrt{6}} \right)$$

of Hardy and Ramanujan [9] we obtain for $1 \leq t \leq n^{\frac{3}{4}-\varepsilon}$, that

$$(8.3) \quad \begin{aligned} \frac{p(n-t)}{p(n)} &= (1 + o(1)) \exp \left(- \frac{2\pi}{\sqrt{6}} (\sqrt{n} - \sqrt{n-t}) \right) \\ &= (1 + o(1)) \exp \left(- \frac{\pi t}{\sqrt{6n}} \right) \exp \left(- \frac{2\pi}{\sqrt{6}} \left(\frac{t}{\sqrt{n} + \sqrt{n-t}} - \frac{t}{2\sqrt{n}} \right) \right) \\ &= (1 + o(1)) \exp \left(- \frac{\pi t}{\sqrt{6n}} \right) \exp \left(- \frac{2\pi t}{\sqrt{6}} \frac{\sqrt{n} - \sqrt{n-t}}{2\sqrt{n}(\sqrt{n} + \sqrt{n-t})} \right) \\ &= (1 + o(1)) \exp \left(- \frac{\pi t}{\sqrt{6n}} \right) \exp \left(O(t^2 n^{-3/2}) \right) = (1 + o(1)) \exp \left(- \frac{\pi t}{\sqrt{6n}} \right). \end{aligned}$$

The equalities (8.3) and (8.2) give Corollary 8.1.

9. Local stability of $\Pi_d(n, \mathcal{R})$.

The next corollary says that if we take two sets $\mathcal{R} = \{N_1, \dots, N_d\} \subset \mathbb{Z}^d$ verifying (8.1) and $\mathcal{R}^* = \{N_1^*, \dots, N_d^*\} \subset \mathbb{R}^d$ such that the N_r^* are near the N_r on average, then in the estimation of $\Pi_d(n, \mathcal{R})$ we may replace the N_r by the N_r^* in cost of an admissible error term. This will be very useful for the proofs of the different results announced in the introduction.

Corollary 9.1. *For $0 < \varepsilon < 10^{-2}$, $n \geq n_1$, $d \leq (n - n^{3/4})^{\frac{1}{8}-\varepsilon}$, $n \equiv R \pmod{d}$, and two sets $\mathcal{R} = \{N_1, \dots, N_d\} \subset \mathbb{Z}^d$, $\mathcal{R}^* = \{N_1^*, \dots, N_d^*\} \subset \mathbb{R}^d$ such that:*

- (i) \mathcal{R} satisfies (8.1);
- (ii) \mathcal{R} and \mathcal{R}^* verify

$$(9.1) \quad \sum_{r=1}^d |N_r - N_r^*| \leq d^3,$$

we have

$$\Pi_d(n, \mathcal{R}) = (1 + o(1))p(n)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}} \right)^{\frac{d-1}{2}} \exp \left\{ - \frac{\pi R^*}{\sqrt{6n}} - \frac{\sqrt{6n}}{\pi d} \sum_{r=1}^d \exp \left(- \frac{dN_r^* \pi}{\sqrt{6n}} \right) \right\}.$$

Proof. Let F be the function defined by :

$$(9.2) \quad F(N_1, \dots, N_d) = \exp \left\{ - \frac{\pi R}{\sqrt{6n}} - \frac{\sqrt{6n}}{\pi d} \sum_{r=1}^d \exp \left(- \frac{dN_r \pi}{\sqrt{6n}} \right) \right\}.$$

If \mathcal{R}^* satisfy (9.1), then in Corollary 8.1, $F(N_1, \dots, N_r) \sim F(N_1^*, \dots, N_d^*)$ since

$$\left| \frac{1}{\sqrt{n}} \sum_{r=1}^d r(N_r - N_r^*) \right| \leq \frac{1}{\sqrt{n}} \sum_{r=1}^d d|N_r - N_r^*| \leq \frac{d^4}{\sqrt{n}} = o(1),$$

and

$$\begin{aligned} \left| \frac{\sqrt{n}}{d} \sum_{r=1}^d \left(\exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right) - \exp\left(-\frac{dN_r^*\pi}{\sqrt{6n}}\right) \right) \right| &\leq \frac{\sqrt{n}}{d} \sum_{r=1}^d \exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right) \\ &\quad \times \left| 1 - \exp\left(-\frac{d(N_r^* - N_r)\pi}{\sqrt{6n}}\right) \right| \\ &\leq \frac{\sqrt{n}}{d} \sum_{r=1}^d n^{-\frac{3}{8} - \frac{\varepsilon}{2}} O\left(\frac{d}{\sqrt{n}} |N_r^* - N_r|\right) \\ &= O(d^3 n^{-\frac{3}{2} - \frac{\varepsilon}{2}}) = o(1). \end{aligned}$$

This ends the proof of Corollary 9.1.

10. Partitions without abnormally represented residue classes; proof of Corollary 1.2

If we shall sum over certain choices of N_1, \dots, N_d then the product in

$$F(N_1, \dots, N_d) = \prod_{r=1}^d \exp\left\{ -\frac{\pi r N_r}{\sqrt{6n}} - \frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{dN_r\pi}{\sqrt{6n}}\right) \right\}$$

would be useful for an “independent” computation but we have the condition

$$(10.1) \quad N_1 \equiv n - \sum_{r=2}^d r N_r \pmod{d}.$$

For $N_1^* = \lfloor \frac{N_1}{d} \rfloor d$ (or $\lceil \frac{N_1}{d} \rceil d$) and $N_r^* = N_r$ ($r = 2, \dots, d$), Corollary 9.1 implies that in an asymptotic sense, we can substitute the condition (10.1) by the condition $d|N_1$. Let $A := \lceil (\frac{3}{4} + \varepsilon) \frac{\sqrt{6}}{2\pi d^2} \sqrt{n} \log n \rceil d$ and $B := \lfloor \frac{\sqrt{6n}^{5/8}}{\pi d^2} \rfloor d$.

Thus $d|A$, $d|B$, and

$$\left(\frac{3}{4} + \varepsilon\right) \frac{\sqrt{6n}}{2\pi d} \log n \leq A < B \leq \frac{\sqrt{6n}^{5/8}}{\pi d}.$$

In the following lines, for each $A \leq N_1, \dots, N_d < B$, \mathcal{R} is the associated set $\mathcal{R} = \{N_1, \dots, N_d\}$ and the integer R is $\sum_{r=1}^d r N_r$. By Corollary 9.1,

$$\sum_{\substack{A \leq N_1, \dots, N_d < B \\ R \equiv n \pmod{d}}} \Pi_d(n, \mathcal{R}) = (1 + o(1)) p(n) d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}}\right)^{\frac{d-1}{2}} \sum_{\substack{A \leq N_1, \dots, N_d < B \\ d|N_1}} F(N_1, \dots, N_d).$$

Here the sum is

$$\begin{aligned} S &:= \sum_{\substack{A/d \leq N'_1 < B/d \\ A \leq N_2, \dots, N_d < B}} F(dN'_1, N_2, \dots, N_d) \\ &= \sum_{\substack{A/d \leq N'_1 < B/d \\ A \leq N_2, \dots, N_d < B}} \int_{N'_1}^{N'_1+1} \int_{N_2}^{N_2+1} \cdots \int_{N_d}^{N_d+1} F(dN'_1, N_2, \dots, N_d) dt'_1 dt_2 \cdots dt_d. \end{aligned}$$

Next we apply Corollary 9.1

$$S = \sum_{\substack{A/d \leq N'_1 < B/d \\ A \leq N_2, \dots, N_d < B}} \int_{N'_1}^{N'_1+1} \int_{N_2}^{N_2+1} \cdots \int_{N_d}^{N_d+1} (1 + o(1)) F(dt'_1, t_2, \dots, t_d) dt'_1 \cdots dt_d,$$

since $(dt'_1 - dN'_1) + (t_2 - N_2) + \cdots + (t_d - N_d) \leq d + d - 1 \leq d^3$.

By $dt'_1 = t_1$, it is

$$\begin{aligned} S &= (1 + o(1)) \frac{1}{d} \int_A^B \int_A^B \cdots \int_A^B F(t_1, \dots, t_d) dt_1 \cdots dt_d \\ &= (1 + o(1)) \frac{1}{d} \prod_{r=1}^d \int_A^B \exp\left(-\frac{\pi r t}{\sqrt{6n}} - \frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{dt\pi}{\sqrt{6n}}\right)\right) dt. \end{aligned}$$

We set $t = u\sqrt{6n}/\pi d$ in the integral :

$$S = (1 + o(1)) \frac{1}{d} \left(\frac{\sqrt{6n}}{\pi d}\right)^d \prod_{r=1}^d \int_{A\pi d/\sqrt{6n}}^{B\pi d/\sqrt{6n}} e^{-\frac{ur}{d}} e^{-\frac{e^{-u}\sqrt{6n}}{\pi d}} du.$$

Next we write $x = \frac{\sqrt{6n}}{\pi d} e^{-u}$

$$\begin{aligned} S &= (1 + o(1)) \frac{1}{d} \left(\frac{\sqrt{6n}}{\pi d}\right)^{d - \sum_{r=1}^d \frac{r}{d}} \prod_{r=1}^d \int_{\frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{A\pi d}{\sqrt{6n}}\right)}^{\frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{B\pi d}{\sqrt{6n}}\right)} x^{\frac{r}{d}-1} e^{-x} dx \\ &= (1 + o(1)) \frac{1}{d} \left(\frac{\sqrt{6n}}{\pi d}\right)^{\frac{d-1}{2}} \prod_{r=1}^d \int_{\frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{A\pi d}{\sqrt{6n}}\right)}^{\frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{B\pi d}{\sqrt{6n}}\right)} x^{\frac{r}{d}-1} e^{-x} dx. \end{aligned}$$

We shall estimate the complementary integrals:

$$\begin{aligned} \int_0^{\frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{B\pi d}{\sqrt{6n}}\right)} x^{\frac{r}{d}-1} e^{-x} dx &= \int_0^{\exp(-n^{1/8} + o(1))\sqrt{6n}/(\pi d)} x^{\frac{r}{d}-1} e^{-x} dx \\ &< \int_0^{\sqrt{nd}^{-1} \exp(-n^{\frac{1}{8}})} x^{\frac{r}{d}-1} dx = \frac{d}{r} \left(\frac{\sqrt{n}}{d} \exp(-n^{1/8})\right)^{\frac{r}{d}} \\ &\leq \frac{d}{r} \left(\exp\left(\frac{\log n}{2} - n^{1/8}\right)\right)^{r/d} \leq \frac{d}{r} \exp\left(-\frac{n^{1/8}}{2d}\right) \\ &\leq \frac{d}{r} \exp\left(-\frac{n^\varepsilon}{2}\right) = O\left(\Gamma\left(\frac{r}{d}\right)\right) \exp\left(-\frac{n^\varepsilon}{2}\right) \\ &= o\left(\frac{1}{d}\right) \Gamma\left(\frac{r}{d}\right), \end{aligned}$$

by

$$\Gamma(x) = \frac{1}{xe^{\gamma x}} \prod_{\nu=1}^{\infty} \frac{e^{x/\nu}}{1 + \frac{x}{\nu}} > \frac{1}{xe^{\gamma x}},$$

where γ is the Euler constant.

For the other side, we have:

$$\begin{aligned}
\int_{\frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{A\pi d}{\sqrt{6n}}\right)}^{\infty} x^{\frac{r}{d}-1} e^{-x} dx &= \int_{\exp\left(-\left(\frac{3}{8}+\frac{\varepsilon}{2}\right)\log n+o(1)\right)\frac{\sqrt{6n}}{\pi d}}^{\infty} x^{\frac{r}{d}-1} e^{-x} dx \\
&= \int_{(1+o(1))\frac{\sqrt{6}}{\pi} n^{\frac{1}{8}-\frac{\varepsilon}{2}}}{\infty} x^{\frac{r}{d}-1} e^{-x} dx \\
&\leq \int_{\frac{n^{\frac{\varepsilon}{2}}}{2}}^{\infty} x^{\frac{r}{d}-1} e^{-x} dx \leq \int_{\frac{n^{\frac{\varepsilon}{2}}}{2}}^{\infty} e^{-x} dx \\
&\leq \exp\left(-\frac{n^{\frac{\varepsilon}{2}}}{2}\right) = o\left(\frac{1}{d}\right) = o\left(\frac{1}{d}\right)\Gamma\left(\frac{r}{d}\right),
\end{aligned}$$

since $\Gamma\left(\frac{r}{d}\right) \geq 1$.

Finally we obtain that

$$\begin{aligned}
\sum_{\substack{A \leq N_1, \dots, N_d < B \\ R \equiv n \pmod{d}}} \Pi_d(n, \mathcal{R}) &= (1+o(1))p(n)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}}\right)^{\frac{d-1}{2}} \frac{1}{d} \left(\frac{\sqrt{6n}}{\pi d}\right)^{\frac{d-1}{2}} \\
&\times \prod_{r=1}^d \left\{ \Gamma\left(\frac{r}{d}\right) + o\left(\frac{1}{d}\right)\Gamma\left(\frac{r}{d}\right) \right\} \\
&= (1+o(1))p(n)\sqrt{d} \left(\frac{1}{2\pi}\right)^{\frac{d-1}{2}} (1+o(d^{-1}))^d \prod_{r=1}^d \Gamma\left(\frac{r}{d}\right) \\
&= (1+o(1))p(n) \frac{\Gamma\left(\frac{1}{d}\right) \cdots \Gamma\left(\frac{d-1}{d}\right)}{\frac{(2\pi)^{\frac{d-1}{2}}}{\sqrt{d}}} \\
&= (1+o(1))p(n).
\end{aligned}$$

11. Partitions with equilibrated residue classes: proof of Corollary 1.3

For $1 \leq a < b \leq d$, we can estimate the number of partitions of n with the property that the residue classes a and $b \pmod{d}$ contain the same number of summands. Let $E(a, b)$ denote the set of such partitions. By Corollary 1.2, apart from $o(p(n))$ partitions of n we may assume that $A \leq N_1, \dots, N_d < B$. Thus we have:

$$E(a, b) = \sum_{\substack{A \leq N_1, \dots, N_d \leq B \\ n \equiv R \pmod{d} \\ N_a = N_b}} \Pi_d(n, \mathcal{R}) + o(p(n)).$$

We can follow the proof of Corollary 1.2 to make the N_1, \dots, N_d independent.

There is a technical difficulty when d is small (when $\varphi(d) < 3$). We would like to replace for some convenient $j \in \{1, \dots, d\} \setminus \{a, b\}$ the condition

$$jN_j \equiv n - \sum_{\substack{1 \leq r \leq d \\ r \neq j}} rN_r \pmod{d}$$

by $d|N_j^*$. But in this way, when d is small we are not sure that the correspondence between the corresponding sets \mathcal{R} and \mathcal{R}^* is one-to-one.

We will choose our set \mathcal{R}^* in the following way. If $a \neq 1$ then we take $N_1^* = d \lfloor \frac{N_1}{d} \rfloor$.

If $a = 1$, $b \neq d - 1$ and $d \geq 3$ then we use $j = d - 1$, $N_{d-1}^* = d \lfloor \frac{N_{d-1}}{d} \rfloor$.

If $a = 1$, $b = d - 1$ and $d \notin \{2, 3, 4, 6\}$ we use $j = c$, $N_c^* = d \lfloor \frac{N_c}{d} \rfloor$ with c minimal satisfying $1 < c < d - 1$ and $(c, d) = 1$.

If $(a, b, d) = (1, 5, 6)$, we use $N_2^* = 3 \lfloor \frac{N_2}{3} \rfloor$, $N_3^* = 2 \lfloor \frac{N_3}{2} \rfloor$ (thus in this case we have $\mathcal{R}^* = \{N_1, N_2^*, N_3^*, N_4, N_5, N_6\}$).

The cases $(a, b, d) \in \{(1, 2, 2), (1, 2, 3), (1, 3, 4)\}$ are to be investigated separately. Later we have to substitute

$$\int_A^B \exp\left(-\frac{\pi}{\sqrt{6n}}at_a - \frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{dt_a\pi}{\sqrt{6n}}\right)\right) dt_a \int_A^B \exp\left(-\frac{\pi}{\sqrt{6n}}bt_b - \frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{dt_b\pi}{\sqrt{6n}}\right)\right) dt_b$$

by

$$\int_A^B \exp\left(-\frac{\pi}{\sqrt{6n}}(a+b)t - 2\frac{\sqrt{6n}}{\pi d} \exp\left(-\frac{dt\pi}{\sqrt{6n}}\right)\right) dt;$$

moreover, $\Gamma(\frac{a}{d})\Gamma(\frac{b}{d})$ by

$$\frac{\pi d}{\sqrt{6n}} \int_0^\infty x^{\frac{a+b}{d}-1} e^{-2x} dx = \frac{\pi d}{\sqrt{6n}} \frac{\Gamma(\frac{a+b}{d})}{2^{\frac{a+b}{d}}}.$$

The complementary integrals change unessentially.

Thus the final result is

$$\begin{aligned} o(p(n)) + (1 + o(1))p(n) \frac{\pi d}{\sqrt{6n}} 2^{-\frac{a+b}{d}} \frac{\Gamma(\frac{a+b}{d})}{\Gamma(\frac{a}{d})\Gamma(\frac{b}{d})} \\ = o(p(n)) + O\left(p(n) \frac{d^2}{\sqrt{n}}\right) = o(p(n)), \end{aligned}$$

we have used the facts that $\Gamma(\frac{a}{d})\Gamma(\frac{b}{d}) \geq 1$, $\Gamma(\frac{a+b}{d}) \leq \Gamma(\frac{1}{d}) = d\Gamma(\frac{1}{d} + 1) \leq d$.

This result is valid for $(a, b, d) = (1, 2, 2)$ too. For $(a, b, d) \in \{(1, 2, 3), (1, 3, 4)\}$ we can obtain similar expressions weighted by constants depending on the residue of $n \pmod d$: $0, 0, 3; 0, 2, 0, 2$.

12. Comparison between the number of summands in two residue classes: proof of Theorem 1.4

12.1. Proof of the propositions (i) and (ii) of Theorem 1.4

In this section, for $1 \leq a < b \leq d$, we investigate the number of partitions of n in which there are more parts $\equiv a \pmod d$ than parts $\equiv b \pmod d$, briefly the case $N_a > N_b$. We shall consider the cases $N_a > N_b$ resp. $N_a \geq N_b$ together as $N_a \geq N_b + \Delta$ with $\Delta = 1$ resp. $\Delta = 0$.

By Corollary 1.2 the N_r belong to $[A, B]$ for almost partitions :

$$\sum_{\substack{N_1, \dots, N_d \\ R \equiv n \pmod d \\ N_a \geq N_b + \Delta}} \Pi_d(n, \mathcal{R}) = o(p(n)) + \sum_{\substack{A \leq N_1, \dots, N_d < B \\ R \equiv n \pmod d \\ N_a \geq N_b + \Delta}} \Pi_d(n, \mathcal{R}).$$

Apart from $(a, b, d) \in \{(1, 2, 2), (1, 2, 3), (1, 3, 4)\}$ - as in the proof of Corollary 1.3 - we can suppose that $1 < a$ and follow the proof of Corollary 1.2.

We have to substitute:

$$\sum_{A \leq N_a < B} \sum_{A \leq N_b < B} \int_{N_a}^{N_a+1} \int_{N_b}^{N_b+1} F(\dots, t_a, \dots, t_b, \dots) dt_a dt_b$$

by

$$T_{a,b} := \sum_{A+\Delta \leq N_a < B} \sum_{A \leq N_b \leq N_a - \Delta} \int_{N_a}^{N_a+1} \int_{N_b}^{N_b+1} F(\dots, t_a, \dots, t_b, \dots) dt_a dt_b.$$

We have

$$T_{a,b} = \sum_{\Delta+A \leq N_a < B} \int_{N_a}^{N_a+1} \int_A^{N_a+1-\Delta} F(\dots, t_a, \dots, t_b, \dots) dt_a dt_b.$$

When $\Delta = 1$ we have the upper bound

$$T_{a,b} \leq \int_A^B \int_A^{t_a} F(\dots, t_a, \dots, t_b, \dots) dt_a dt_b.$$

If $\Delta = 0$, then it is a lower bound :

$$T_{a,b} \geq \int_A^B \int_A^{t_a} F(\dots, t_a, \dots, t_b, \dots) dt_a dt_b.$$

Taking into account Corollary 1.3, apart from $o(p(n))$ partitions of n , we can compute both cases substituting $\int_{A \leq t_a \leq B} \int_{A \leq t_b \leq B}$ by $\int_{A \leq t_a \leq B} \int_{A \leq t_b \leq t_a}$. Later, considering also the complementary integrals, we have to substitute

$$(1 + o(d^{-1}))\Gamma\left(\frac{a}{d}\right)(1 + o(d^{-1}))\Gamma\left(\frac{b}{d}\right)$$

by

$$\int_0^\infty x^{\frac{a}{d}-1} e^{-x} \left(\int_x^\infty y^{\frac{b}{d}-1} e^{-y} dy \right) dx + o(d^{-1})\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right).$$

For $(a, b, d) \in \{(1, 2, 2), (1, 2, 3), (1, 3, 4)\}$ we use both $N_1^* = d \lfloor \frac{N_1}{d} \rfloor$, $N_1^{**} = \lceil \frac{N_1}{d} \rceil d$.

Thus the final result is

(12.1)

$$\sum_{\substack{N_1, \dots, N_d \\ R \equiv n \pmod{d} \\ N_a \geq N_b + \Delta}} \Pi_d(n, \mathcal{R}) = o(p(n)) + \frac{(1 + o(1))}{\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right)} p(n) \int_0^\infty x^{\frac{a}{d}-1} e^{-x} \int_x^\infty y^{\frac{b}{d}-1} e^{-y} dy dx.$$

This ends the proofs of (i) and (ii) of Theorem 1.4.

12.2. Proof of the lower bound (1.6)

For the special case $1 \leq a < b = d$, (12.1) becomes

$$o(p(n)) + \frac{(1 + o(1))p(n)}{\Gamma\left(\frac{a}{d}\right)\Gamma(1)} \int_0^\infty x^{\frac{a}{d}-1} e^{-2x} dx = o(p(n)) + \frac{(1 + o(1))p(n)}{2^{\frac{a}{d}}} = (1 + o(1)) \frac{p(n)}{2^{\frac{a}{d}}},$$

since $1 < 2^{\frac{a}{d}} < 2$.

Moreover,

$$\frac{1}{2^{\frac{a}{d}}} \geq \frac{1}{2^{\frac{(d-1)}{d}}} = \frac{1}{2} \exp\left(\frac{\log 2}{d}\right) > \frac{1}{2} + \frac{\log 2}{2d}.$$

For the general case $1 \leq a < b \leq d$ let us consider the integrals

$$I_1 = \int_0^\infty x^{\frac{a}{d}-1} e^{-x} \left(\int_x^\infty y^{\frac{b}{d}-1} e^{-y} dy \right) dx$$

and

$$I_2 = \int_0^\infty x^{\frac{b}{d}-1} e^{-x} \left(\int_x^\infty y^{\frac{a}{d}-1} e^{-y} dy \right) dx.$$

Then we have $I_1 + I_2 = \Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right)$ and

$$I_1 - I_2 = \int_0^\infty \int_x^\infty e^{-x-y} (xy)^{\frac{a}{d}-1} (y^{\frac{b-a}{d}} - x^{\frac{b-a}{d}}) dy dx > 0.$$

Therefore, $I_1 > \frac{1}{2}\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right)$ and

$$o(p(n)) + (1 + o(1))p(n) \frac{I_1}{\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right)} \sim p(n) \frac{I_1}{\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right)}.$$

We can estimate

$$\frac{I_1}{\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right)} - \frac{1}{2} = \frac{I_1 - I_2}{2\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right)}$$

from below in the following way. For any $\delta > 0$,

$$\begin{aligned} I_1 - I_2 &> \int_0^\infty \int_{x(1+\delta)}^\infty e^{-x-y} (xy)^{\frac{a}{d}-1} (y^{\frac{b-a}{d}} - x^{\frac{b-a}{d}}) dy dx \\ &\geq \int_0^\infty \int_{x(1+\delta)}^\infty e^{-x-y} (xy)^{\frac{a}{d}-1} \left(y^{\frac{b-a}{d}} - \left(\frac{y}{1+\delta}\right)^{\frac{b-a}{d}} \right) dy dx \\ &= \left(1 - \frac{1}{(1+\delta)^{\frac{b-a}{d}}}\right) \int_0^\infty \int_{x(1+\delta)}^\infty x^{\frac{a}{d}-1} e^{-x} y^{\frac{b}{d}-1} e^{-y} dy dx \\ &= \left(1 - \frac{1}{(1+\delta)^{\frac{b-a}{d}}}\right) \left\{ I_1 - \int_0^\infty \int_x^{x(1+\delta)} x^{\frac{a}{d}-1} e^{-x} y^{\frac{b}{d}-1} e^{-y} dy dx \right\} \\ &> \left(1 - \frac{1}{(1+\delta)^{\frac{b-a}{d}}}\right) \left\{ \frac{1}{2}\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right) - \int_0^\infty x^{\frac{a}{d}-1} e^{-x} \int_x^{x(1+\delta)} y^{\frac{b}{d}-1} e^{-y} dy dx \right\} \\ &\geq \left(1 - \frac{1}{(1+\delta)^{\frac{b-a}{d}}}\right) \left\{ \frac{1}{2}\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right) - \int_0^\infty x^{\frac{a}{d}-1} e^{-x} (x^{\frac{b}{d}-1} e^{-x} \delta x) dx \right\} \\ &= \left(1 - \frac{1}{(1+\delta)^{\frac{b-a}{d}}}\right) \left\{ \frac{1}{2}\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right) - \delta \Gamma\left(\frac{a+b}{d}\right) 2^{-\frac{a+b}{d}} \right\}, \end{aligned}$$

We obtain

$$\frac{I_1 - I_2}{2\Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right)} > \left(1 - \frac{1}{(1+\delta)^{\frac{b-a}{d}}}\right) \left\{ \frac{1}{4} - \frac{\delta \Gamma\left(\frac{a+b}{d}\right)}{2^{1+\frac{a+b}{d}} \Gamma\left(\frac{a}{d}\right)\Gamma\left(\frac{b}{d}\right)} \right\}.$$

For $x, y > 0$,

$$\frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)} = B(x, y) = \int_0^1 t^{x-1}(1-t)^{y-1} dt.$$

For $0 < x \leq y \leq 1$, we get $B(x, y) \geq \int_0^1 t^{x-1} dt = \frac{1}{x}$ and $\frac{\Gamma(x+y)}{\Gamma(x)\Gamma(y)} \leq x$. Further,

$$x4^{-x} \leq \frac{1}{\log 4} 4^{\frac{-1}{\log 4}} = \frac{1}{2e \log 2}.$$

Therefore,

$$\frac{\delta \Gamma\left(\frac{a+b}{d}\right)}{2^{1+\frac{a+b}{d}} \Gamma\left(\frac{a}{d}\right) \Gamma\left(\frac{b}{d}\right)} \leq \frac{\delta \frac{a}{d}}{2^{1+\frac{2a}{d}+\frac{b-a}{d}}} \leq \frac{\delta}{2^{\frac{b-a}{d}}} \frac{1}{4e \log 2}.$$

Let $\alpha := 0.59$ and

$$\delta := \left(\frac{1}{1 - \alpha \frac{b-a}{d}} \right)^{\frac{d}{b-a}} - 1.$$

Then

$$\begin{aligned} \frac{\delta}{2^{\frac{b-a}{d}}} &= 2^{-\frac{b-a}{d}} \exp\left(\frac{d}{b-a} \log \frac{1}{1 - \alpha \frac{b-a}{d}}\right) - 2^{-\frac{b-a}{d}} \\ &= 2^{-\frac{b-a}{d}} \exp\left(\alpha + \sum_{m=2}^{\infty} \frac{1}{m} \alpha^m \left(\frac{b-a}{d}\right)^{m-1}\right) - 2^{-\frac{b-a}{d}} \\ &\leq 2^{-\frac{b-a}{d}} \exp\left(\alpha + \left(\log \frac{1}{1 - \alpha} - \alpha\right) \frac{b-a}{d}\right) - 2^{-\frac{b-a}{d}} \\ &= \exp\left(\alpha - \left(\log 2 + \alpha - \log \frac{1}{1 - \alpha}\right) \frac{b-a}{d}\right) - \exp\left(-(\log 2) \frac{b-a}{d}\right) \end{aligned}$$

which is monotonically decreasing in $\frac{b-a}{d}$ (for $\alpha = 0.59$). Therefore

$$\frac{\delta}{2^{\frac{b-a}{d}}} \leq e^\alpha - 1.$$

Finally,

$$\left(1 - \frac{1}{(1+\delta)^{\frac{b-a}{d}}}\right) \left\{ \frac{1}{4} - \frac{\delta}{2^{\frac{b-a}{d}}} \frac{1}{4e \log 2} \right\} \geq \alpha \frac{b-a}{d} \frac{1}{4} \left(1 - \frac{e^\alpha - 1}{e \log 2}\right) > \frac{1}{12} \frac{b-a}{d}.$$

We remind the reader of the fact that we considered the cases $N_a > N_b$ resp. $N_a \geq N_b$ together. Increasing ε , we can use $d \leq n^{\frac{1}{8}-\varepsilon}$. Thus (1.6) is proved.

12.3. Proof of the upper bound (1.7)

For $1 \leq a, b \leq d$, we denote by $S_{a,b}$ the set of the partitions of n satisfying $N_a \geq N_b$.

As it is said in the introduction, when $b = d$, we can compute $|S_{a,d}|$ by (1.5), $|S_{a,d}| = p(n)(2^{-\frac{a}{d}} + o(1))$. The upper bound (1.7) in Theorem 1.4 is a consequence of the following lemma :

Lemma 12.1. *For $1 \leq a < b < d$, we have $|S_{a,b}| \leq |S_{a,d}| + o(p(n))$.*

Proof.

For any $1 \leq c_1, c_2, c_3 \leq d$, let $S(c_1, c_2, c_3)$ denote the set of the partitions of n such that $N_{c_1} \geq N_{c_2} \geq N_{c_3}$ (here as before, N_{c_i} is the number of parts $\equiv c_i \pmod{d}$).

We have the two equalities :

$$S_{a,b} = S(a, b, d) \cup S(a, d, b) \cup S(d, a, b),$$

and

$$S_{a,d} = S(a, b, d) \cup S(a, d, b) \cup S(b, a, d).$$

By Corollary 1.3, $|S(c_1, c_2, c_3) \cap S(c_{\sigma(1)}, c_{\sigma(2)}, c_{\sigma(3)})| = o(p(n))$ for any non trivial permutation σ on the set $\{1, 2, 3\}$. Thus we have :

$$\begin{aligned} |S_{a,b}| &= |S(a, b, d)| + |S(a, d, b)| + |S(d, a, b)| + o(p(n)), \\ |S_{a,d}| &= |S(a, b, d)| + |S(a, d, b)| + |S(b, a, d)| + o(p(n)). \end{aligned}$$

To prove Lemma 12.1, it is sufficient to show that

$$(12.2) \quad |S(d, a, b)| \leq |S(b, a, d)| + o(p(n)).$$

To prove this inequality, we will show that there exists an injective map Ψ defined on $S(d, a, b)$ such that for almost all partitions $\Pi \in S(d, a, b)$, $\Psi(\Pi) \in S(b, a, d)$. This map consists in exchanging the parts $\equiv b \pmod{d}$ with the parts $\equiv d \pmod{d}$ and to put some appropriate parts to compensate the quantity $(d-b)(N_d - N_b)$ arising from this exchange. Such sort of idea was already used in some proofs of [2].

• We suppose that $a \neq 1$. Let Π be a generic partition of n in $S(d, a, b)$. We write Π in the following way :

$$\Pi : n = \sum_{r=1}^d \sum_{j=1}^{N_r} (r + \lambda_{j,r}d) \text{ with } \lambda_{j,r} \geq 0, \text{ for } 1 \leq r \leq d, 1 \leq j \leq N_r,$$

so that for $1 \leq r \leq d$, $r + \lambda_{1,r}d, \dots, r + \lambda_{N_r,r}d$ are the parts $\equiv r \pmod{d}$. To this partition Π we assign the following partition $\Psi(\Pi)$

$$\Psi(\Pi) : n = \sum_{r=1}^d \sum_{j=1}^{M_r} (r + \mu_{j,r}d) \text{ with } \mu_{j,r} \geq 0, (1 \leq r \leq d, 1 \leq j \leq M_r),$$

with

$$M_r = \begin{cases} N_r & \text{if } r \notin \{1, b, d\} \\ N_d & \text{if } r = b \\ N_b & \text{if } r = d \\ N_1 + (d-b)(N_d - N_b) & \text{if } r = 1, \end{cases}$$

and the integers $\mu_{j,r}$ are defined by :

$$\begin{aligned} \mu_{j,r} &= \lambda_{j,r} \text{ for } r \notin \{1, b, d\}, 1 \leq j \leq M_r, \\ \mu_{j,b} &= \lambda_{j,d} (1 \leq j \leq M_b), \mu_{j,d} = \lambda_{j,b} (1 \leq j \leq M_d), \\ \mu_{j,1} &= \begin{cases} \lambda_{j,1} & \text{if } 1 \leq j \leq N_1 \\ 0 & \text{if } N_1 + 1 \leq j \leq M_1. \end{cases} \end{aligned}$$

We check easily that this application Ψ is injective, and that we have $M_b \geq M_a \geq M_d$, $\Psi(\Pi) \in S(b, a, d)$.

• Case $a = 1$. If $a = 1$, the above application is not good because it may happen that $M_a = M_1 = N_1 + (d-b)(N_d - N_b) > M_b$, $\Psi(\Pi) \notin S(b, a, d)$.

In the case $a = 1$, we transform the quantity $(d-b)(N_d - N_b)$ in parts equal to 2 and eventually add a part equal to 1. We set $Z = \lfloor \frac{(N_d - N_b)(d-b)}{2} \rfloor$. The partition $\Psi(\Pi)$ is defined by :

$$\text{for } r \notin \{1, 2, b, d\}, M_r = N_r \text{ and } \mu_{j,r} = \lambda_{j,r} \text{ for } 1 \leq j \leq M_r,$$

$$M_d = N_b \text{ and } \mu_{j,d} = \lambda_{j,b} \text{ for } 1 \leq j \leq M_d,$$

$$M_1 = \begin{cases} N_1 & \text{if } (N_d - N_b)(d - b) \equiv 0 \pmod{2} \\ N_1 + 1 & \text{if } (N_d - N_b)(d - b) \equiv 1 \pmod{2} \end{cases}, \mu_{j,1} = \lambda_{j,1} \text{ for } 1 \leq j \leq N_1,$$

and if $(N_d - N_b)(d - b) \equiv 1 \pmod{2}$, $\mu_{N_1+1,1} = 0$.

If $b \neq 2$, then we take

$$M_b = N_d \text{ and } \mu_{j,b} = \lambda_{j,d} \text{ for } 1 \leq j \leq M_b,$$

$$M_2 = N_2 + Z \text{ and } \mu_{j,2} = \begin{cases} \lambda_{j,2} & \text{if } 1 \leq j \leq N_2 \\ 0 & \text{if } N_2 + 1 \leq j \leq M_2. \end{cases}$$

If $b = 2$, then we take

$$M_2 = N_d + Z \text{ and } \mu_{j,2} = \begin{cases} \lambda_{j,d} & \text{if } 1 \leq j \leq N_d \\ 0 & \text{if } N_d + 1 \leq j \leq M_2. \end{cases}$$

In all cases we have $M_b \geq M_d$, and $M_a \geq M_d$. Furthermore, we have $M_1 \leq N_1 + 1 \leq N_d + 1$ thus the situation $M_1 > M_b$ can happen only if $N_d = N_1$. By Corollary 1.3, this can arrive for at most $o(p(n))$ partitions of n . Thus $\Psi(\Pi) \in S(b, a, d)$ for almost all $\Pi \in S(d, a, b)$. This ends the proof of Lemma 12.1.

Thus Theorem 1.4 is proved.

13. Dominant residue class

We investigate the number of partitions of n in which there are more parts $\equiv a \pmod{d}$ than parts $\equiv b \pmod{d}$ for all $b \in \{1, \dots, d\} \setminus \{a\}$, briefly the case $N_a > N_b$ for $1 \leq b \leq d$, $b \neq a$. We shall consider the cases $N_a > N_b$ ($b \neq a$) resp. $N_a \geq N_b$ ($b \neq a$) together as $N_a \geq N_b + \Delta$ ($b \neq a$) with $\Delta = 1$ resp. $\Delta = 0$.

We have to estimate

$$M_a := \sum_{\substack{N_1, \dots, N_d \\ R \equiv n \pmod{d} \\ N_a \geq \Delta + \max_{b \neq a} N_b}} \Pi_d(n, R).$$

Like in the proof of Corollary 1.3 or Theorem 1.4 we apply Corollary 1.2 to avoid the abnormally small or big N_r and Corollary 9.1 to make the N_r independent.

Lemma 13.1. *We have the equality :*

$$(13.1) \quad M_a = o(p(n)) + (1 + o(1))p(n)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}} \right)^{\frac{d-1}{2}} \sum_{\substack{A \leq N_1, \dots, N_d < B \\ d | N_1 \\ N_a \geq \Delta + \max_{b \neq a} N_b}} F(N_1, \dots, N_d).$$

We use both $N_1^* = \lfloor \frac{N_1}{d} \rfloor d$ and $N_1^{**} = \lceil \frac{N_1}{d} \rceil d$.

We first state the case $a = 1$, next we will quote the modifications to handle the case $a \geq 2$.

By Corollary 9.1 and Corollary 1.2 we have

$$(13.2) \quad M_1 = o(p(n)) + (1 + o(1))p(n)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}} \right)^{\frac{d-1}{2}} \sum_{\substack{A \leq N_1, \dots, N_d < B \\ R \equiv n \pmod{d} \\ N_1 \geq \Delta + \max_{b \neq 1} N_b}} F(N_1^*, \dots, N_d)$$

$$= o(p(n)) + (1 + o(1))p(n)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}} \right)^{\frac{d-1}{2}} \sum_{\substack{A \leq N_1, \dots, N_d \leq B \\ R \equiv n \pmod{d} \\ N_1 \geq \Delta + \max_{b \neq 1} N_b}} F(N_1^{**}, \dots, N_d).$$

We have

$$(13.3) \quad \sum_{\substack{A \leq N_1, \dots, N_d < B \\ N_1 \equiv n - \sum_{r=2}^d r N_r \pmod{d} \\ N_1 \geq \Delta + \max_{2 \leq b \leq d} N_b}} F(N_1^*, \dots, N_d) \geq \sum_{\substack{A \leq N_1, \dots, N_d < B \\ N_1 \equiv n - \sum_{r=2}^d r N_r \pmod{d} \\ N_1^* \geq \Delta + \max_{2 \leq b \leq d} N_b}} F(N_1^*, \dots, N_d) \\ = \sum_{\substack{A \leq N_1^*, \dots, N_d < B \\ N_1^* \geq \Delta + \max_{2 \leq b \leq d} N_b}} F(N_1^*, \dots, N_d)$$

and

$$(13.4) \quad \sum_{\substack{A \leq N_1, \dots, N_d \leq B \\ N_1 \equiv n - \sum_{r=2}^d r N_r \pmod{d} \\ N_1 \geq \Delta + \max_{2 \leq b \leq d} N_b}} F(N_1^{**}, \dots, N_d) \leq \sum_{\substack{A \leq N_1, \dots, N_d \leq B \\ N_1 \equiv n - \sum_{r=2}^d r N_r \pmod{d} \\ N_1^{**} \geq \Delta + \max_{2 \leq b \leq d} N_b}} F(N_1^{**}, \dots, N_d) \\ \leq \sum_{\substack{A \leq N_1^{**}, \dots, N_d \leq B \\ N_1^{**} \geq \Delta + \max_{2 \leq b \leq d} N_b}} F(N_1^{**}, \dots, N_d) \\ \leq \sum_{\substack{A \leq N_1^{**}, \dots, N_d < B \\ N_1^{**} \geq \Delta + \max_{2 \leq b \leq d} N_b}} F(N_1^{**}, \dots, N_d) + E,$$

where E is an error term collecting the (N_1^{**}, \dots, N_d) with $N_1^{**} = B$. This term is small enough by Corollary 1.2. Therefore

$$M_1 = o(p(n)) + (1 + o(1))p(n)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}} \right)^{\frac{d-1}{2}} \sum_{\substack{A \leq N_1, \dots, N_d < B \\ d|N_1 \\ N_1 \geq \Delta + \max_{b \neq 1} N_b}} F(N_1, \dots, N_d).$$

This proves (13.1) for $a = 1$. For $a \neq 1$ we replace in (13.2) the conditions $N_1 \geq \Delta + \max_{2 \leq b \leq d} N_b$ by the conditions $N_a \geq \Delta + \max_{b \neq a} N_b$. When we replace in these conditions N_1 by N_1^* and change $\leq B$ to $< B$, the corresponding (13.3) becomes an upper bound and when we replace N_1 by N_1^{**} , (13.4) becomes a lower bound. (The inequalities are permuted). This ends the proof of the lemma.

Proof of (i) and (ii) of Theorem 1.5 for $a = 1$. It remains to compute the summations of

$$T_1 := \sum_{\substack{A \leq dN'_1, N_2, \dots, N_d < B \\ dN'_1 \geq N_b + \Delta \\ b=2, \dots, d}} F(dN'_1, N_2, \dots, N_d).$$

We have :

$$T_1 = \sum_{\substack{A \leq dN'_1, N_2, \dots, N_d < B \\ dN'_1 \geq N_b + \Delta \\ b=2, \dots, d}} \int_{N'_1}^{N'_1+1} \int_{N_2}^{N_2+1} \cdots \int_{N_d}^{N_d+1} F(dN'_1, N_2, \dots, N_d) dt'_1 dt_2 \cdots dt_d.$$

We apply one more times Corollary 9.1 :

$$\begin{aligned} T_1 &= (1 + o(1)) \sum_{\substack{A \leq dN'_1, N_2, \dots, N_d < B \\ dN'_1 \geq N_b + \Delta \\ b=2, \dots, d}} \int_{N'_1}^{N'_1+1} \int_{N_2}^{N_2+1} \cdots \int_{N_d}^{N_d+1} F(dt'_1, t_2, \dots, t_d) dt'_1 dt_2 \cdots dt_d. \\ &= (1 + o(1)) \sum_{\frac{\Delta+A}{d} \leq N'_1 < \frac{B}{d}} \int_{N'_1}^{N'_1+1} \int_A^{dN'_1-\Delta+1} \cdots \int_A^{dN'_1-\Delta+1} F(dt'_1, t_2, \dots, t_d) dt'_1 dt_2 \cdots dt_d. \end{aligned}$$

Here the sum is

$$\leq \int_{\frac{A}{d}}^{\frac{B}{d}} \left(\int_A^{dt'_1} \cdots \int_A^{dt'_1} F(dt'_1, t_2, \dots, t_d) dt_2 \cdots dt_d \right) dt'_1$$

if $\Delta = 1$ resp.

$$\begin{aligned} &\geq \int_{\frac{A+d}{d}}^{\frac{B}{d}} \left(\int_A^{dt'_1-d} \cdots \int_A^{dt'_1-d} F(dt'_1, t_2, \dots, t_d) dt_2 \cdots dt_d \right) dt'_1 \\ &= \int_{\frac{A}{d}}^{\frac{B-d}{d}} \left(\int_A^{dt'_1} \cdots \int_A^{dt'_1} F(dt'_1 + d, t_2, \dots, t_d) dt_2 \cdots dt_d \right) dt'_1 \end{aligned}$$

if $\Delta = 0$. Taking into account Corollary 1.3, apart from $o(dp(n))$ partitions of n we can compute both cases together for fixed d as

$$\begin{aligned} T_1 &= o(p(n)) + (1 + o(1))p(n)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}} \right)^{\frac{d-1}{2}} \\ &\quad \times \frac{1}{d} \int_A^B \left(\int_A^{t_1} \cdots \int_A^{t_1} F(t_1, \dots, t_d) dt_2 \cdots dt_d \right) dt_1 \\ &= o(p(n)) + (1 + o(1))p(n)d^{\frac{2+d}{2}} \left(\frac{1}{2\sqrt{6n}} \right)^{\frac{d-1}{2}} \\ &\quad \times \frac{1}{d} \int_A^B \exp \left(-\frac{\pi}{\sqrt{6n}} t_1 - \frac{\sqrt{6n}}{\pi d} \exp \left(-\frac{dt_1 \pi}{\sqrt{6n}} \right) \right) \\ &\quad \times \left\{ \prod_{r=2}^d \int_A^{t_1} \exp \left(-\frac{\pi}{\sqrt{6n}} r t - \frac{\sqrt{6n}}{\pi d} \exp \left(-\frac{dt \pi}{\sqrt{6n}} \right) \right) dt \right\} dt_1 \\ &= o(p(n)) + \frac{(1 + o(1))p(n)}{\Gamma\left(\frac{1}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)} \int_0^\infty x^{\frac{1}{d}-1} e^{-x} \left(\prod_{r=2}^d \int_x^\infty y^{\frac{r}{d}-1} e^{-y} dy \right) dx \end{aligned}$$

for fixed d . This ends the proof of Theorem 1.5 (i) and (ii) in the case $a = 1$.

Case $a \geq 2$. The term corresponding to T_1 is

$$T_a := \sum_{\substack{A \leq dN'_1, \dots, N_d < B \\ N_a \geq \Delta + dN'_1 \\ N_a \geq \Delta + \max_{b \neq \{1, a\}} N_b}} F(dN'_1, N_2, \dots, N_d).$$

We use the integral representation and we apply Corollary 9.1 :

$$\begin{aligned} T_a &= (1 + o(1)) \\ &\quad \times \sum_{A+\Delta \leq N_a < B} \int_{N_a}^{N_a+1} \int_{A/d}^{\frac{N_a-\Delta}{d}+1} \left[\int_A^{N_a-\Delta+1} \cdots \int_A^{N_a-\Delta+1} F(dt'_1, \dots, t_d) \prod_{j \neq 1, a} dt_j \right] dt'_1 dt_a. \end{aligned}$$

By Corollary 1.3 we see that we can handle the cases $\Delta = 0$ and 1 together and we do the same computations as in the case $a = 1$.

14. Some properties of truncated Gamma functions; end of the proof of Theorem 1.5

For $1 \leq a \leq d$, let us consider the integrals

$$J_a = \int_0^\infty x^{\frac{a}{d}-1} e^{-x} \left(\prod_{\substack{r=1 \\ r \neq a}}^d \int_x^\infty y^{\frac{r}{d}-1} e^{-y} dy \right) dx.$$

We have

$$\prod_{j=1}^d \Gamma\left(\frac{j}{d}\right) = \prod_{j=1}^d \left(\int_0^\infty x_j^{\frac{j}{d}-1} e^{-x_j} dx_j \right) = J_1 + J_2 + \cdots + J_d,$$

since

$$\{(x_1, \dots, x_d) \in [0, \infty[^d] = \cup_{a=1}^d \{(x_1, \dots, x_d) \in [0, \infty[^d, x_a = \min_{1 \leq j \leq d} x_j\}.$$

For $1 < a \leq d$,

$$J_1 - J_a = \int_0^\infty \left(\int_x^\infty e^{-x-y} (xy)^{\frac{1}{d}-1} (y^{\frac{a-1}{d}} - x^{\frac{a-1}{d}}) \left(\prod_{\substack{r=2 \\ r \neq a}}^d \int_x^\infty z^{\frac{r}{d}-1} e^{-z} dz \right) dy \right) dx > 0.$$

Therefore,

$$J_1 > \frac{1}{d} \Gamma\left(\frac{1}{d}\right) \Gamma\left(\frac{2}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)$$

and

$$o(p(n)) + (1 + o(1))p(n) \frac{J_1}{\Gamma\left(\frac{1}{d}\right) \Gamma\left(\frac{2}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)} \sim p(n) \frac{J_1}{\Gamma\left(\frac{1}{d}\right) \Gamma\left(\frac{2}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)}$$

for fixed $d \geq 2$. We can estimate

$$\frac{J_1}{\Gamma\left(\frac{1}{d}\right) \Gamma\left(\frac{2}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)} - \frac{1}{d} = \frac{\sum_{a=2}^d (J_1 - J_a)}{d \Gamma\left(\frac{1}{d}\right) \Gamma\left(\frac{2}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)}$$

from below in the following way. For any $\delta > 0$ and $2 \leq a \leq d$,

$$\begin{aligned} J_1 - J_a &> \int_0^\infty \left(\int_{x(1+\delta)}^\infty e^{-x-y} (xy)^{\frac{1}{d}-1} \left(y^{\frac{a-1}{d}} - \left(\frac{y}{1+\delta} \right)^{\frac{a-1}{d}} \right) \right. \\ &\quad \times \left. \left(\prod_{\substack{r=2 \\ r \neq a}}^d \int_x^\infty z^{\frac{r}{d}-1} e^{-z} dz \right) dy \right) dx \\ &= \left(1 - \frac{1}{(1+\delta)^{\frac{a-1}{d}}} \right) \left\{ J_1 \right. \\ &\quad \left. - \int_0^\infty x^{\frac{1}{d}-1} e^{-x} \left(\int_x^{x(1+\delta)} y^{\frac{a}{d}-1} e^{-y} dy \right) \left(\prod_{\substack{r=2 \\ r \neq a}}^d \int_x^\infty z^{\frac{r}{d}-1} e^{-z} dz \right) dx \right\} \\ &> \left(1 - \frac{1}{(1+\delta)^{\frac{a-1}{d}}} \right) \left\{ \frac{1}{d} \Gamma\left(\frac{1}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right) - \delta \Gamma\left(\frac{1+a}{d}\right) 2^{-\frac{1+a}{d}} \prod_{\substack{r=2 \\ r \neq a}}^d \Gamma\left(\frac{r}{d}\right) \right\}, \end{aligned}$$

$$\begin{aligned} \frac{J_1 - J_a}{d\Gamma\left(\frac{1}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)} &> \left(1 - \frac{1}{(1+\delta)^{\frac{a-1}{d}}}\right) \left\{ \frac{1}{d^2} - \frac{\delta\Gamma\left(\frac{1+a}{d}\right)}{2^{\frac{1+a}{d}} d\Gamma\left(\frac{1}{d}\right)\Gamma\left(\frac{a}{d}\right)} \right\} \\ &> \frac{\exp\left(\frac{a-1}{d} \log(1+\delta)\right) - 1}{(1+\delta)^{\frac{a-1}{d}}} \left\{ \frac{1}{d^2} - \frac{\delta}{d^2} \right\} > \frac{a-1}{d^3} \frac{(1-\delta) \log(1+\delta)}{1+\delta}. \end{aligned}$$

Choosing $\delta := 0.364$ we obtain that

$$\sum_{a=2}^d \frac{J_1 - J_a}{d\Gamma\left(\frac{1}{d}\right)\Gamma\left(\frac{2}{d}\right) \cdots \Gamma\left(\frac{d}{d}\right)} > \sum_{a=2}^d \frac{a-1}{7d^3} = \frac{1}{14} \left(\frac{1}{d} - \frac{1}{d^2} \right).$$

This ends the proof of Theorem 1.5.

Similar arguments yield estimates for the case $N_1 > N_2 > \dots > N_d$, *i. e.*, for the number of “ d -regular” partitions of n , and more generally to obtain estimates for Theorem 1.7.

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