ACTA ARITHMETICA
XCII.3 (2000)

The number of powers of 2 in a representation of large even integers by sums of such powers and of two primes

by

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1. Main results. The Goldbach conjecture is that every integer not less than 6 is a sum of two odd primes. The conjecture still remains open. Let $E(x)$ denote the number of positive even integers not exceeding x which cannot be written as a sum of two prime numbers. In 1975 Montgomery and Vaughan [9] proved that

$$E(x) \ll x^{1-\theta}$$

for some small computable constant $\theta > 0$. In [4] the author proved that $E(x) \ll x^{0.921}$, and recently [5] he improved that to $E(x) \ll x^{0.914}$.

In 1951 and 1953, Linnik [6, 7] established the following "almost Goldbach" result.

Every large positive even integer N is a sum of two primes p_1, p_2 and a bounded number of powers of 2, i.e.

$$N = p_1 + p_2 + 2^{\nu_1} + \ldots + 2^{\nu_k}. \tag{1.1}$$

Let $r_k''(N)$ denote the number of representations of N in the form (1.1). In [8] Liu, Liu and Wang proved that for any $k \geq 54000$, there exists $N_k > 0$ depending on k only such that if $N \geq N_k$ is an even integer then

$$r_k''(N) \gg N(\log N)^{k-2}. \tag{1.2}$$

In this paper we prove the following result.

THEOREM 1. *For any integer $k \geq 25000$, there exists $N_k > 0$ depending on k only such that if $N \geq N_k$ is an even integer then*

$$r_k''(N) \gg N(\log N)^{k-2}.$$

2000 *Mathematics Subject Classification*: 11P32, 11P55.

Project supported by The National Natural Science Foundation of China.

Let $r'_k(n)$ denote the number of representations of an odd integer n in the form

$$n = p + 2^{\nu_1} + \ldots + 2^{\nu_k}. \tag{1.3}$$

The second purpose of this paper is to establish the following result.

THEOREM 2. *For any $\varepsilon > 0$, there exists a constant k_0 depending on ε only such that if $k \geq k_0$ and $N \geq N_k$ then*

$$\sum_{2\nmid n\leq N} (r'_k(n) - 2(\log_2 N)^k(\log N)^{-1})^2 \leq \varepsilon 2N(\log_2 N)^{2k}(\log N)^{-2}.$$

In particular, for $\varepsilon = 0.9893$, one can take $k_0 = 12500$.

In what follows, $\mathcal{L}$ always stands for $\log PT$, and $L(s,\chi)$ denotes the Dirichlet L-function. δ denotes a positive constant which is arbitrarily small but not necessarily the same at each occurrence.

2. Some lemmas. Let N be a large integer, and set

$$P := N^{\theta}, \qquad T := P^3(\log N)^6, \qquad Q := P^{-1}N(\log N)^{-3}, \tag{2.1}$$

where θ is an absolute constant. Let $\chi \pmod q), \chi_0 \pmod q)$ be a character and a principal character mod q respectively.

LEMMA 1. *Let χ be a non-principal character mod q. Then for any $\varepsilon > 0$ there exists a $\delta = \delta(\varepsilon) > 0$ such that*

$$-\Re\frac{L'}{L}(s,\chi) \leq -\sum_{|1+it-\varrho|\leq\delta} \Re\frac{1}{s-\varrho} + \left(\frac{3}{16}+\varepsilon\right)H$$

uniformly for

$$1 + \frac{1}{H\log H} \leq \sigma \leq 1 + \frac{\log H}{H}$$

providing that q is sufficiently large, where $H = \log q(|t|+2)$ and $s = \sigma + it$.

This is Lemma 2.4 of [3].

For a real number α, set $\alpha^* = \alpha\mathcal{L}^{-1}$ and let

$$\varrho_j = 1 - \lambda_j^* + i\gamma_j^*, \qquad j = 1, 2, \ldots,$$

denote the non-trivial zeros of $L(s,\chi)$ with $|\gamma_j| \leq T\mathcal{L}$, where λ_j are in increasing order.

LEMMA 2. *Let N be sufficiently large. Then no function $L(s,\chi)$ with χ primitive mod $q \leq P$, except for a possible exceptional one only, has a zero in the region*

$$\sigma \geq 1 - \frac{0.239}{\mathcal{L}}, \qquad |t| \leq T.$$

If the exceptional function, denoted by $L(s,\widetilde{\chi})$, exists, then $\widetilde{\chi}$ must be a real primitive character mod $\widetilde{q}$, $\widetilde{q} \le P$, and $L(s,\widetilde{\chi})$ has a real simple zero $\widetilde{\beta}$; no other function $L(s,\chi)$ with χ primitive mod $q \le P$ has a zero in the region

$$\sigma \ge 1 - \frac{0.517}{\mathcal{L}}, \qquad |t| \le T.$$

P r o o f. If $q_1, q_2 \le P$, $q_1 \ne q_2$, consider the zeros of $L(s,\chi_{q_1})$ and $L(s,\chi_{q_2})$ for non-principal characters χ_{q_1} and χ_{q_2}. If ϱ_1 is a zero of $L(s,\chi_{q_1})$ and ϱ_2 is a zero of $L(s,\chi_{q_2})$, then as in Lemma 3.7 of [3] and setting $\eta = a\sqrt{N}/\mathcal{L}$, $\sigma = \eta + 1$, note that $T = P^3(\log N)^6$, $\log P^2T = (5/4+\delta)\mathcal{L}$. Then for any positive constant a we have

$$G(0) - G\left(-\frac{\lambda_1}{a}\right) - G\left(-\frac{\lambda_2}{a}\right) + a\left(\frac{39}{64} + \varepsilon\right) \ge 0$$

where

$$G(z) = \int_0^\infty \exp\left\{-\frac{1}{4}x^2 + zx\right\} dx.$$

Take $a = 1.22$; then $\lambda_1 \le 0.239$ implies $\lambda_2 > 0.63$. Take $a = 1.26$; then $\lambda_1 \le 0.411$, implies $\lambda_2 > 0.411$. If $q_1 = q_2$, by Lemma 3.7 and Theorem 1.2 of [3] the lemma follows.

LEMMA 3. *Suppose χ is a real non-principal character mod $q \le P$, and ϱ_1 is real. Then $\lambda_2 > 0.8$.*

P r o o f. By Lemma 3.2 of [3] the assertion follows.

By Lemma 4 of [5] we have

LEMMA 4. *Let χ be a non-principal character mod $q \le P$, and ϱ_1, ϱ_2, ϱ_3 be the zeros of $L(s,\chi)$. Then*

$$\lambda_2 > 0.575, \qquad \lambda_3 > 0.618.$$

LEMMA 5. *Let $\chi \ne \chi_0$ be a character mod $q \le P$. Let n_0, n_1, n_2 denote the numbers of zeros of $L(s,\chi)$ in the rectangles*

$$\begin{aligned} R_0 &: \quad 1 - \mathcal{L}^{-1} \le \sigma \le 1 - 0.239\mathcal{L}^{-1},\ |t - t_0| \le 5.8\mathcal{L}^{-1},\\ R_1 &: \quad 1 - 5\mathcal{L}^{-1} \le \sigma \le 1 - 0.239\mathcal{L}^{-1},\ |t - t_1| \le 23.4\mathcal{L}^{-1},\\ R_2 &: 1 - \lambda_+\mathcal{L}^{-1} \le \sigma \le 1 - 0.239\mathcal{L}^{-1},\ |t - t_2| \le 23.4\mathcal{L}^{-1}, \end{aligned}$$

respectively, where t_0, t_1, t_2 are real numbers satisfying $|t_i| \le T$, and $5 < \lambda_+ \le \log\log\mathcal{L}$. Then

$$n_0 \le 3, \qquad n_1 \le 10, \qquad n_2 \le 0.2292(\lambda_+ + 42.9).$$

P r o o f. It is well known that

$$-\frac{\zeta'}{\zeta}(\sigma) - \Re\frac{L'}{L}(s,\chi) \ge 0$$

where $\sigma = \Re s$.

We consider the rectangle R_0. Let $s = \sigma + it_0$, $\sigma = 1 + 8.4\mathcal{L}^{-1}$, and denote by $\varrho = 1 - \lambda^* + i\gamma$ the zero of $L(s,\chi)$ in R_0. Hence $0.239 \le \lambda \le 1, |\gamma - t_0| \le 5.8\mathcal{L}^{-1}$. So we have

$$-\Re\frac{1}{s-\varrho} = -\mathcal{L}\frac{8.4+\lambda}{(8.4+\lambda)^2 + ((\gamma - t_0)\mathcal{L})^2} \le -\mathcal{L}\frac{9.4}{9.4^2 + 5.8^2}.$$

By Lemma 1,

$$-\Re\frac{L'}{L}(s,\chi) \le -\sum_{|1+it_0-\varrho|\le\delta} \Re\frac{1}{s-\varrho} + 0.18751\mathcal{L}.$$

If $|1+it_0-\varrho| > \delta$ then $\Re\frac{1}{s-\varrho} = O(1)$. So

$$-\Re\frac{L'}{L}(s,\chi) \le \mathcal{L}\biggl(0.18751 - \frac{9.4n_0}{9.4^2+5.8^2}\biggr).$$

Since $-\frac{\zeta'}{\zeta}(\sigma) \le \frac{1}{\sigma-1} + A$, where A is an absolute constant, we have

$$\frac{9.4n_0}{9.4^2+5.8^2} \le \frac{1}{8.4} + 0.18752, \qquad n_0 \le 3.$$

Now as above, let $\sigma = 1 + 24\mathcal{L}^{-1}$. Then $n_1 \le 10$ and $n_2 \le 0.2292(\lambda_+ + 42.9)$.

3. The zero density estimate of the Dirichlet L-function. In this section we use the notations of Section 3 of [8]. For $1 \le j \le 4$, let h_j denote positive constants satisfying $h_1 < h_2 < h_3, h_2+h_4+3/8 < h_3, 2h_4+3/8 < h_1$.

Let

$$z_j := (P^2T)^{h_j}, \qquad \alpha := 1 - \lambda\mathcal{L}^{-1}, \qquad \lambda \le \log\log\mathcal{L}, \tag{3.1}$$

$$D(\lambda, T) := D := \{s = \sigma + it : \alpha \le \sigma \le 1 - 0.239\mathcal{L}^{-1},\ |t| \le T\}. \tag{3.2}$$

Let $N(\chi,\alpha,T)$ denote the number of zeros of $L(s,\chi)$ in D, and

$$N^*(\alpha,P,T) = \sum_{q\le P}\ \sideset{}{^*}\sum_{\chi\,(\mathrm{mod}\,q)} N(\chi,\alpha,T), \tag{3.3}$$

where $\sum^*_{\chi\,(\mathrm{mod}\,q)}$ indicates that the sum is over primitive characters mod q.

For positive δ_1, δ_3, let

$$\begin{aligned}\kappa(s) := s^{-2}\{&(e^{-(1-\delta_1)(\log z_1)s} - e^{-(\log z_1)s})\delta_3(\log z_3)\\ &- (e^{-(\log z_3)s} - e^{-(1+\delta_3)(\log z_3)s})\delta_1(\log z_1)\}.\end{aligned} \tag{3.4}$$

For a zero $\varrho_0 \in D$, let

$$M(\varrho_0) := \sum_{\varrho(\chi)} |\kappa(\varrho(\chi) + \overline{\varrho}_0 - 2\alpha)|, \tag{3.5}$$

where the sum is over the zeros of $L(s,\chi)$ in D. If $2h_4+3/8<(1-\delta_1)h_1$, then as in (3.17) of [8] we have

$$N^*(\alpha,P,T) \le \frac{(1+\delta)\max_{\varrho_0} M(\varrho_0)}{2(1-\alpha)(h_2-h_1)\delta_1\delta_3h_1h_3h_4(\log P^2T)^4}(P^2T)^{2h_3(1-\alpha)}. \tag{3.6}$$

(i) If $5<\lambda\le\log\log\mathcal{L}$, let $\varDelta=23.4\mathcal{L}^{-1}$. Then as in [8], by Lemma 5 we have

$$M(\varrho_0)\le 0.2292(\lambda+42.9)(\log P^2T)^3(1/2) \times\{(\delta_1h_1(2\delta_3+\delta_3^2)h_3^2-\delta_3h_3(2\delta_1-\delta_1^2)h_1^2)+(\pi/23.4)^2(\delta_1h_1+\delta_3h_3)\}.$$

Choose $h_1=0.58$, $h_2=0.669$, $h_3=1.08$, $h_4=0.0353$, $\delta_1h_1=\delta_3h_3=\pi/23.4$. By (3.6) we have

$$N^*(\alpha,P,T)\le 268.6(P^2T)^{2.16(1-\alpha)}. \tag{3.7}$$

(ii) If $1<\lambda\le 5$, then as in [8], by Lemma 5 ($n_1\le 10$) we have

$$M(\varrho_0)\le(10/2)(\log P^2T)^3 \times\{(\delta_1h_1(2\delta_3+\delta_3^2)h_3^2-\delta_3h_3(2\delta_1-\delta_1^2)h_1^2)+(\pi/23.4)^2(\delta_1h_1+\delta_3h_3)\}.$$

Choose $h_1=0.82, h_2=1.179, h_3=1.71, h_4=0.155, \delta_1h_1=\delta_3h_3=\pi/23.4$. By (3.6) we have

$$N^*(\alpha,P,T)\le(104.1/\lambda)(P^2T)^{3.42(1-\alpha)}. \tag{3.8}$$

(iii) If $0.618<\lambda\le 1$, for $a=6.3$ we have

$$\left(\frac{1}{a}-\frac{1}{a+1}-\frac{2(a+1)}{(a+1)^2+5.8^2}+0.1876\right) \times\max\left\{\frac{a+1}{5.8^2}+\frac{1}{a+1},\frac{a+0.618}{5.8^2}+\frac{1}{a+0.618}\right\}\le 0.014621.$$

As in [8], by Lemma 5 we have

$$M(\varrho_0)\le\{1.5(\delta_1h_1(2\delta_3+\delta_3^2)h_3^2-\delta_3h_3(2\delta_1-\delta_1^2)h_1^2) + 2\cdot 0.014621\cdot(\delta_1h_1+\delta_3h_3)\}(\log P^2T)^3.$$

Choose $h_1=1.0065$, $h_2=1.599$, $h_3=2.25$, $h_4=0.2759$, $\delta_1=0.079$, $\delta_3=0.094$. By (3.6) we have

$$N^*(\alpha,P,T)\le(14.3/\lambda)(P^2T)^{4.5(1-\alpha)}. \tag{3.9}$$

(iv) If $0.575<\lambda\le 0.618$, by Lemma 4 there are at most two zeros satisfying $\varrho=1-\beta/\mathcal{L}-i\gamma/\mathcal{L}$, $\beta<0.618$. As in (v) of [8], we have

$$N^*(\alpha,P,T)\le\frac{(1+\delta)\widetilde{M}}{2(1-\alpha)(h_2-h_1)h_4\log P^2T}(P^2T)^{2h_3(1-\alpha)} \tag{3.10}$$

where

$$\widetilde{M} := \max_{\substack{\chi \bmod q \\ q \le P}} \max_{1 \le j \le 2} \frac{1}{j} \int_{\log z_1}^{\log z_3} \Big| \sum_{l=1}^{j} e^{-(\varrho(l,\chi)-\alpha)x} \Big|^2 \, dx,$$

and $\varrho(l,\chi)$ is a zero of $L(s,\chi)$ in D. We have

$$\int_{\log z_1}^{\log z_3} |e^{-(\varrho(l,\chi)-\alpha)x}|^2 \, dx \le (h_3 - h_1) \log P^2 T,$$

$$\frac{1}{2} \int_{\log z_1}^{\log z_3} \Big| \sum_{l=1}^{2} e^{-(\varrho(l,\chi)-\alpha)x} \Big|^2 \, dx \le 2(h_3 - h_1) \log P^2 T.$$

Choose $h_1 = 0.9, h_2 = 1.4525, h_3 = 2.09, h_4 = 0.2624$. By (3.10) we have

$$N^*(\alpha, P, T) \le (8.21/\lambda)(P^2T)^{4.18(1-\alpha)}.$$

(v) If $0.411 < \lambda \le 0.575$, by Lemma 4 there is at most one zero satisfying $\varrho = 1 - \beta/\mathcal{L} - i\gamma/\mathcal{L}$, $\beta < 0.575$. As in (v) of [8], we have

$$N^*(\alpha, P, T) \le \frac{(1+\delta)(h_3 - h_1)^2}{(h_2 - h_1)h_4} (P^2T)^{2h_3(1-\alpha)}. \tag{3.11}$$

Choose $h_1 = 1.01, h_2 = 1.4074, h_3 = 2.1, h_4 = 0.3174$. By (3.11) we have

$$N^*(\alpha, P, T) \le 9.42(P^2T)^{4.2(1-\alpha)}.$$

In conclusion we have

Lemma 6. *If $N^*(\alpha, P, T)$ and $\alpha = 1 - \lambda\mathcal{L}^{-1}$ are defined by* (3.3), (3.1), *then*

$$N^*(\alpha, P, T) \le \begin{cases} 2, & \lambda \le 0.411, \\ 9.42(P^2T)^{4.2(1-\alpha)}, & 0.411 < \lambda \le 0.575, \\ 14.28(P^2T)^{4.18(1-\alpha)}, & 0.575 < \lambda \le 0.618, \\ 23.14(P^2T)^{4.5(1-\alpha)}, & 0.618 < \lambda \le 1, \\ 104.1(P^2T)^{3.42(1-\alpha)}, & 1 < \lambda \le 5, \\ 268.6(P^2T)^{2.16(1-\alpha)}, & 5 < \lambda \le \log\log\mathcal{L}. \end{cases}$$

4. The proof of the theorems. By Dirichlet's lemma on rational approximations, each $\alpha \in [Q^{-1}, 1 + Q^{-1}]$ may be written in the form

$$\alpha = a/q + \lambda, \qquad |\lambda| \le (qQ)^{-1}, \tag{4.1}$$

for some positive integers a, q with $1 \le a \le q, (a,q) = 1$ and $q \le Q$. We denote by $I(a,q)$ the set of α satisfying (4.1), and put

$$E_1 = \bigcup_{q \le P} \bigcup_{\substack{a=1 \\ (a,q)=1}}^{q} I(a,q), \qquad E_2 = [Q^{-1}, 1 + Q^{-1}] - E_1.$$

When $q \le P$ we call $I(a,q)$ a *major arc*. By (2.1), all major arcs are mutually disjoint. Let $e(\alpha) = \exp(i2\pi\alpha)$ and $S(\alpha) = \sum_{p\le N} e(p\alpha)$.

Let $\sigma(n)$ denote the singular series in the Goldbach problem, i.e.

$$\sigma(n) := \prod_{p\mid n}(1+(p-1)^{-1})\prod_{p\nmid n}(1-(p-1)^{-2}) \gg 1$$

for even n. Let

$$J(n) := \sum_{\substack{1<n_1,n_2\le N\\ n_1-n_2=n}} (\log n_1 \log n_2)^{-1}.$$

For $0<\theta<1/30$, define

$$\begin{aligned}
(4.2)\qquad f(\theta) :=& \frac{268.6(1-(6+\delta)\theta)}{1-(16.8+\delta)\theta}\exp\left(-\frac{5-(84+\delta)\theta}{(4+\delta)\theta}\right)\\
&+\frac{104.1(1-(6+\delta)\theta)}{1-(23.1+\delta)\theta}\\
&\times\left\{\exp\left(-\frac{1-(23.1+\delta)\theta}{(4+\delta)\theta}\right)-\exp\left(-\frac{5(1-(23.1+\delta)\theta)}{(4+\delta)\theta}\right)\right\}\\
&+\frac{23.14(1-(6+\delta)\theta)}{1-(28.5+\delta)\theta}\\
&\times\left\{\exp\left(-\frac{0.618(1-(28.5+\delta)\theta)}{(4+\delta)\theta}\right)-\exp\left(-\frac{1-(28.5+\delta)\theta}{(4+\delta)\theta}\right)\right\}\\
&+\frac{14.28(1-(6+\delta)\theta)}{1-(26.9+\delta)\theta}\\
&\times\left\{\exp\left(-\frac{0.575(1-(26.9+\delta)\theta)}{(4+\delta)\theta}\right)-\exp\left(-\frac{0.618(1-(26.9+\delta)\theta)}{(4+\delta)\theta}\right)\right\}\\
&+\frac{9.42(1-(6+\delta)\theta)}{1-(27+\delta)\theta}\\
&\times\left\{\exp\left(-\frac{0.411(1-(27+\delta)\theta)}{(4+\delta)\theta}\right)-\exp\left(-\frac{0.575(1-(27+\delta)\theta)}{(4+\delta)\theta}\right)\right\}\\
&+2\left\{\exp\left(-\frac{0.239(1-(6+\delta)\theta)}{(4+\delta)\theta}\right)-\exp\left(-\frac{0.411(1-(6+\delta)\theta)}{(4+\delta)\theta}\right)\right\}
\end{aligned}$$

and

$$(4.3)\qquad F(\theta) := \frac{5.094\pi(1+\delta)}{\sqrt{6}\{1-(6+\delta)\theta\}}f(\theta)+\frac{5.094\pi^2(1+\delta)}{4\sqrt{6}\{1-(6+\delta)\theta\}^2}f^2(\theta).$$

THEOREM 3. *Let n with $|n| \le N^2$ be a non-zero integer, and P, Q satisfy* (2.1). *If $\theta < 1/30$, then for even n we have*

$$\int_{E_1} |S(\alpha)|^2 e(n\alpha)\, d\alpha = \sigma(n)J(n) + R,$$

where

$$|R| \le |n|N(\phi(|n|)(\log N)^2)^{-1}\{F(\theta) + O(\widetilde{r}\phi((n,\widetilde{r}))/\phi^2(\widetilde{r}))\},$$

with the O term occurring only when there exists $\widetilde{\beta}$ in Lemma 2.

The proof of Theorem 3 is the same as in [8], but we use our Lemmas 1–4, Lemma 6 and the fact that $\prod_{p\ge 5}(1 + 1/(p-1)^2) \le 1.132$ (see page 6 of [1]) so we can replace 5.205 by 5.094.

For the proof of Theorems 1 and 2, as in Lemma 20 in Section 7 of [8], we define

$$\begin{aligned} \Theta := \Theta(\eta) := {} & \frac{1}{\log 2}\eta\csc^2(\pi/8)\log\frac{1}{\eta\csc^2(\pi/8)} \\ & + \frac{1}{\log 2}(1-\eta\csc^2(\pi/8))\log\frac{1}{1-\eta\csc^2(\pi/8)}, \end{aligned}$$

$$H(k) := \min_{9\le E\le L}\left\{1.7811\left(1 - \frac{1}{E\csc^2(\pi/8)}\right)^{2k}\log E + 2.3270\frac{1+\log E}{E}\right\},$$

where $L = \log_2 N$.

Choose $\theta = 1/98$ and $\eta = 1/7758$, so $\Theta(\eta) < \theta$. When $k \ge 12500$, choose $E = 460$ one has $H(k) < 0.03989$, for $c_8 < 2.1967, c_9 < 17.2435$ one has $c_9(1-\eta)^{2k-2} < 0.6873$, $(c_8+\delta)F(\theta) < 0.26202$ and $(c_8+\delta)F(\theta) + H(k) + c_9(1-\eta)^{2k-2} < 0.9893$. As in Section 7 of [8], Theorems 1 and 2 can be proved in the same way as Theorems 1 and 2 in [8].

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Received on 12.2.1999
and in revised form on 28.9.1999 (3537)