

ON WARING'S PROBLEM: THREE CUBES AND A MINICUBE

JÖRG BRÜDERN AND TREVOR D. WOOLEY*

ABSTRACT. We establish that almost all natural numbers n are the sum of four cubes of positive integers, one of which is no larger than $n^{5/36}$. The proof makes use of an estimate for a certain eighth moment of cubic exponential sums, restricted to minor arcs only, of independent interest.

1. INTRODUCTION

It was shown by Davenport [6] in 1939 that almost all natural numbers are the sum of four positive integral cubes, and it is now known that when N is large, the number of positive integers not exceeding N that fail to be thus represented is slightly smaller than $N^{37/42}$ (see [11], [3], [4], [16], [17] for the most recent developments). Since integers congruent to 4 modulo 9 are never the sum of three cubes, this conclusion cannot be refined to one involving fewer summands. A formal application of the circle method predicts an asymptotic formula for the number of representations as the sum of four positive cubes, and this would imply that *all* large integers are thus represented. Indeed, the same heuristic argument suggests that the fourth cube is almost redundant, in that it may be replaced by a cube from a sparse sequence without impairing such conclusions. The purpose of this paper is to investigate representations by sums of four positive cubes, one of which is small.

When n is a natural number and $0 < \theta \leq \frac{1}{3}$, we denote by $r_\theta(n)$ the number of representations of n in the form

$$n = x_1^3 + x_2^3 + x_3^3 + x_4^3, \quad (1.1)$$

with x_1, x_2, x_3, x_4 natural numbers satisfying $x_4 \leq n^\theta$. As intimated above, one anticipates that $r_\theta(n) \sim \Gamma(\frac{4}{3})^3 \mathfrak{S}(n) n^\theta$, where $\mathfrak{S}(n)$ is the familiar singular series associated with sums of four cubes. We recall in this context that $\mathfrak{S}(n) \gg 1$ (see, for example, Exercise 3 of §4.6 of [14]), and hence it is expected that $r_\theta(n) \geq 1$ when n is large. We are able to confirm this expectation for values of θ rather smaller than $\frac{1}{7}$, at least, *for almost all* n .

Theorem 1.1. *When $\theta \geq \frac{5}{36}$, one has $r_\theta(n) \geq 1$ for almost all n .*

2000 *Mathematics Subject Classification.* 11P05, 11P55.

Key words and phrases. Waring's problem, sums of cubes, Hardy-Littlewood method.

*The second author is supported by a Royal Society Wolfson Research Merit Award. This paper was conceived at Kinki University in Osaka, and gestated at the Hausdorff Research Institute in Bonn. The authors are grateful to both institutions for their generous hospitality.

The methods of this paper are capable of showing that the conclusion of this theorem remains valid when θ is slightly smaller than 0.13884, whereas $\frac{5}{36} > 0.13888$. For comparison, it is apparent that whenever n is represented in the shape (1.1), then $x_i \leq n^{1/3}$ ($1 \leq i \leq 4$), and so the conclusion is trivial for $\theta \geq \frac{1}{3}$. One may interpret Theorem 1.1 as asserting that almost all large integers possess a (formal) representation as the sum of at most 3.417 positive cubes. Meanwhile, Theorem 1 of [5] shows that almost all large integers not congruent to 5 modulo 9 are the sum of three positive integral cubes and a sixth power, a conclusion tantamount to one involving 3.5 cubes.

In §6, we show that the anticipated asymptotic formula holds almost always for sums of three cubes and a minicube.

Theorem 1.2. *Suppose that $\frac{1}{4} < \theta \leq \frac{1}{3}$. Then, for almost all n , one has*

$$r_\theta(n) = \Gamma\left(\frac{4}{3}\right)^3 \mathfrak{S}(n) n^\theta + O(n^\theta (\log n)^{-1}).$$

A conclusion equivalent to this theorem in the unrestricted situation with $\theta = \frac{1}{3}$ can be extracted from Theorem 3 of Vaughan [11] by incorporating refinements due to Boklan [1]. We remark that it is unnecessary to restrict the minicube implicit in the representation of n in Theorem 1.2 to be bounded by a pure power n^θ , and that this hypothesis may be removed with some technical elaboration of our basic argument.

We prove Theorems 1.1 and 1.2 using the Hardy-Littlewood method, beginning in §2 with some auxiliary mean value estimates. In §3, we establish an upper bound for a certain eighth moment of cubic exponential sums restricted to minor arcs, an estimate of independent interest. The reader is directed to Theorem 3.1 for details. We lay the foundations for an application of the circle method in §4, deriving a lower bound for the contribution of the major arcs. Then, in §5, we apply Bessel's inequality to relate the exceptional set to a minor arc estimate. Following two pruning processes, the proof of Theorem 1.1 is complete. Although complicated by the limited availability of full-length generating functions to be applied in the analysis of the major arcs, the proof of Theorem 1.2 in §6 is essentially routine. Finally, in §7, we briefly discuss the representation of large natural numbers as the sum of seven positive integral cubes, one of which is restricted to be a minicube.

Throughout, we reserve the letter ε to denote a sufficiently small positive number, and we use P to denote a positive number sufficiently large in terms of ε . The implicit constants in Vinogradov's well-known notation \ll and \gg will depend at most on ε , unless otherwise indicated. Whenever ε appears in a statement, either implicitly or explicitly, we assert that the statement holds for each $\varepsilon > 0$. Note that the "value" of ε may consequently change from statement to statement. Finally, throughout this paper, a variable denoted by the letter p should be interpreted as denoting a prime number congruent to 2 modulo 3.

The authors are grateful to the referee for useful comments.

2. CATALYTIC LEMMATA

As is to be expected when considering problems in which one or more variables are shortened, mean values involving diminishing ranges play a prominent rôle in the arguments that follow. We collect together these basic estimates in this section, and begin now by introducing the cast of exponential sums. We take P to be our basic parameter, a large real number, and then take Q to be an auxiliary parameter with $1 \leq Q \leq P$, to be chosen in due course. Next, we define

$$f(\alpha) = \sum_{P < x \leq 2P} e(\alpha x^3) \quad \text{and} \quad g(\alpha) = \sum_{Q < y \leq 2Q} e(\alpha y^3), \quad (2.1)$$

where, here and throughout, we write $e(z)$ for $e^{2\pi iz}$. Also, with η fixed to be a sufficiently small positive number, we define the set of X^η -smooth numbers not exceeding X by

$$\mathcal{A}(X) = \{n \in [1, X] \cap \mathbb{Z} : \varpi \text{ prime and } \varpi | n \Rightarrow \varpi \leq X^\eta\}.$$

We then take R to be a positive number with $R \leq Q$, and put

$$h(\alpha) = \sum_{z \in \mathcal{A}(R)} e(\alpha z^3).$$

We record for future reference the estimate

$$\int_0^1 |h(\alpha)|^6 d\alpha \ll R^{13/4-\tau}, \quad (2.2)$$

which holds for any positive number τ with $\tau^{-1} > 852 + 16\sqrt{2833} = 1703.6\dots$, as a consequence of Theorem 1.2 of [17].

Our purpose in this section is to record estimates for the three mean values

$$T_1 = \int_0^1 |f(\alpha)^2 g(\alpha)^2 h(\alpha)^6| d\alpha, \quad (2.3)$$

$$T_2 = \int_0^1 |f(\alpha)^2 g(\alpha)^4| d\alpha, \quad (2.4)$$

$$T_3 = \int_0^1 |f(\alpha) g(\alpha) h(\alpha)|^2 d\alpha, \quad (2.5)$$

of use in our subsequent deliberations. We begin with an analysis of T_1 via an auxiliary estimate.

Lemma 2.1. *Whenever $R \leq Q^{2/3}$, one has*

$$\int_0^1 |g(\alpha)^2 h(\alpha)^6| d\alpha \ll QR^{13/4-\tau}.$$

Proof. On considering the underlying diophantine equation, the mean value in question counts the number of integral solutions of the equation

$$y_1^3 - y_2^3 = z_1^3 - z_2^3 + z_3^3 - z_4^3 + z_5^3 - z_6^3, \quad (2.6)$$

with

$$Q < y_1, y_2 \leq 2Q \quad \text{and} \quad z_i \in \mathcal{A}(R) \quad (1 \leq i \leq 6). \quad (2.7)$$

When $y_1 > y_2$, the left hand side of this equation exceeds $3Q^2$, whereas the right hand side is always smaller than $3R^3$. Since $R^3 \leq Q^2$, we conclude that all solutions \mathbf{y}, \mathbf{z} of (2.6) satisfy $y_1 = y_2$, whence

$$\int_0^1 |g(\alpha)^2 h(\alpha)^6| d\alpha \leq Q \int_0^1 |h(\alpha)|^6 d\alpha.$$

The desired conclusion now follows from (2.2). \square

Lemma 2.2. *Suppose that $Q = P^{5/6}$ and $P^{4/11} \leq R \leq P^{14/33-\tau/6}$. Then one has*

$$T_1 \ll P^{1+\varepsilon} QR^{13/4-\tau}.$$

Proof. By considering the diophantine equation underlying the mean value (2.3), we find that T_1 counts the number of integral solutions of the equation

$$x_1^3 - x_2^3 = y_1^3 - y_2^3 + z_1^3 - z_2^3 + z_3^3 - z_4^3 + z_5^3 - z_6^3, \quad (2.8)$$

with $P < x_1, x_2 \leq 2P$, and \mathbf{y}, \mathbf{z} as in (2.7). On making use of Lemma 2.1, one discerns that the diagonal contribution I_0 , arising from those solutions of (2.8) counted by T_1 in which $x_1 = x_2$, satisfies

$$I_0 \ll PQR^{13/4-\tau}. \quad (2.9)$$

For the remaining solutions, it suffices by symmetry to consider the situation wherein $x_1 > x_2$. On substituting $h = x_1 - x_2$, one deduces from (2.8) that

$$3hP^2 < (2Q)^3 + 3R^3 < 9P^{5/2},$$

whence $h < 3P^{1/2}$. Consequently, a consideration of the underlying diophantine equation reveals that the contribution of such solutions is at most

$$I_1 = \int_0^1 \Psi(\alpha) |g(\alpha)^2 h(\alpha)^6| d\alpha, \quad (2.10)$$

where

$$\Psi(\alpha) = \sum_{1 \leq h < 3P^{1/2}} \sum_{P < x \leq 2P} e(\alpha h(3x^2 + 3xh + h^2)).$$

We estimate the integral (2.10) by using the Hardy-Littlewood method. When $a \in \mathbb{Z}$ and $q \in \mathbb{N}$, define the auxiliary major arcs $\mathfrak{N}(q, a)$ by putting

$$\mathfrak{N}(q, a) = \{\alpha \in [0, 1) : |q\alpha - a| \leq PQ^{-3}\},$$

and then take \mathfrak{N} to be the union of the arcs $\mathfrak{N}(q, a)$ with $0 \leq a \leq q \leq P$ and $(a, q) = 1$. Next, define $\Upsilon(\alpha)$ for $\alpha \in [0, 1)$ by taking

$$\Upsilon(\alpha) = (q + Q^3|q\alpha - a|)^{-1},$$

when $\alpha \in \mathfrak{N}(q, a) \subseteq \mathfrak{N}$, and otherwise by putting $\Upsilon(\alpha) = 0$. Then, as a consequence of the lemma in Vaughan [10] combined with a standard transference principle (see Exercise 2 of §2.8 of [14]), one finds that whenever $a \in \mathbb{Z}$ and $q \in \mathbb{N}$ satisfy $(a, q) = 1$ and $|\alpha - a/q| \leq q^{-2}$, one has

$$\Psi(\alpha) \ll P^{3/2+\varepsilon} ((q + Q^3|q\alpha - a|)^{-1} + P^{-1} + (q + Q^3|q\alpha - a|)P^{-5/2})^{1/2}.$$

Hence, on applying Dirichlet's approximation theorem and recalling that $Q = P^{5/6}$, one swiftly arrives at the estimate

$$\Psi(\alpha) \ll P^{3/2+\varepsilon} \Upsilon(\alpha)^{1/2} + P^{1+\varepsilon},$$

valid uniformly for $\alpha \in [0, 1)$. Substituting this upper bound into (2.10), and again applying Lemma 2.1, we conclude that

$$I_1 \ll P^{1+\varepsilon} QR^{13/4-\tau} + P^{3/2+\varepsilon} I_2, \quad (2.11)$$

where

$$I_2 = \int_0^1 \Upsilon(\alpha)^{1/2} |g(\alpha)^2 h(\alpha)^6| d\alpha. \quad (2.12)$$

Next, given a natural number q , we define q_1 to be the largest integer whose cube divides q , and then put $q_0 = q/q_1^3$. The function $\kappa(q)$ defined by taking $\kappa(q) = q_0^{-1/2} q_1^{-1}$ is multiplicative. For future use we define the function $g^+(\alpha)$ for $\alpha \in [0, 1)$ by putting

$$g^+(\alpha) = q\kappa(q)Q\Upsilon(\alpha), \quad (2.13)$$

when $\alpha \in \mathfrak{N}(q, a) \subseteq \mathfrak{N}$, and otherwise by taking $g^+(\alpha) = 0$. On referring to Theorem 4.1 and Lemmata 4.3, 4.4, 4.5 and 6.2 of [14], one readily confirms that the estimate

$$g(\alpha) \ll P^\varepsilon g^+(\alpha) + P^{1/2+\varepsilon} \quad (2.14)$$

holds uniformly for $\alpha \in \mathfrak{N}$. Substituting this bound into (2.12), we deduce that

$$I_2 \ll P^{1/2+\varepsilon} I_3 + P^\varepsilon I_4, \quad (2.15)$$

where

$$I_3 = \int_0^1 \Upsilon(\alpha)^{1/2} |g(\alpha)h(\alpha)^6| d\alpha \quad (2.16)$$

and

$$I_4 = \int_0^1 \Upsilon(\alpha)^{1/2} |g^+(\alpha)g(\alpha)h(\alpha)^6| d\alpha. \quad (2.17)$$

Our investigation of I_3 begins with the application of Lemma 2 of [2]. By hypothesis, we have $R \geq P^{4/11}$, and thus we are led via (2.2) to the bound

$$\int_0^1 \Upsilon(\alpha) |h(\alpha)|^6 d\alpha \ll Q^{\varepsilon-3} \left(P \int_0^1 |h(\alpha)|^6 d\alpha + R^6 \right) \ll Q^{\varepsilon-3} R^6. \quad (2.18)$$

Applying Schwarz's inequality to (2.16), and then applying Lemma 2.1, we therefore see that

$$\begin{aligned} I_3 &\leq \left(\int_0^1 \Upsilon(\alpha) |h(\alpha)|^6 d\alpha \right)^{1/2} \left(\int_0^1 |g(\alpha)^2 h(\alpha)^6| d\alpha \right)^{1/2} \\ &\ll (Q^{\varepsilon-3} R^6)^{1/2} (QR^{13/4-\tau})^{1/2}. \end{aligned} \quad (2.19)$$

We turn our attention next to I_4 . On recalling (2.12), a trivial estimate for $h(\alpha)$ in combination with an application of Hölder's inequality conveys us from (2.17) to the bound

$$I_4 \leq \left(R^6 \int_0^1 g^+(\alpha)^4 d\alpha \right)^{1/4} \left(\int_0^1 \Upsilon(\alpha) |h(\alpha)|^6 d\alpha \right)^{1/4} I_2^{1/2}.$$

In view of our definition (2.13), a routine computation confirms that

$$\int_0^1 g^+(\alpha)^4 d\alpha \ll P^\varepsilon Q.$$

Consequently, on recalling (2.18), we obtain the upper bound

$$I_4 \ll P^\varepsilon Q^{-1/2} R^3 I_2^{1/2}.$$

Again making use of the hypothesis $R \geq P^{4/11}$, we therefore see from (2.15) and (2.19) that

$$I_2 \ll P^{1/2+\varepsilon} Q^{-1} R^{37/8-\tau/2} + P^\varepsilon Q^{-1} R^6 \ll P^\varepsilon Q^{-1} R^6.$$

We substitute this estimate into (2.11) to obtain

$$I_1 \ll P^{1+\varepsilon} Q R^{13/4-\tau} + P^{3/2+\varepsilon} Q^{-1} R^6.$$

A modest computation confirms that the first term here dominates under the hypothesis that $R \leq P^{14/33-\tau/6}$, and thus the conclusion of the lemma follows by reference to (2.9). \square

We next supply an estimate for T_2 by combining routine diminishing ranges arguments.

Lemma 2.3. *When $1 \leq Q \leq P$, one has*

$$T_2 \ll P^\varepsilon (PQ^2 + P^{-1}Q^{9/2}).$$

Moreover, provided that $P^{4/5} \leq Q \leq P$, one has

$$T_2 \ll P^\varepsilon (PQ^2 + P^{-3/2}Q^5).$$

In particular, when $1 \leq Q \leq P^{5/6}$, one has $T_2 \ll P^{1+\varepsilon}Q^2$.

Proof. Write $M = PQ^{-1}$ and $H = PM^{-3}$. Then the argument leading to equation (4) of [10] takes us from (2.4) to the estimate

$$T_2 \ll P^{1+\varepsilon}Q^2 + \int_0^1 \Phi(\alpha) |g(\alpha)|^4 d\alpha,$$

where

$$\Phi(\alpha) = \sum_{1 \leq h \leq 6H} \sum_{P < x \leq 2P} e(\alpha h(3x^2 + 3xh + h^2)).$$

A simple modification of the familiar proof of Hua's lemma (see, for example, the argument on page 438 of [16]) shows that

$$\int_0^1 |\Phi(\alpha)|^4 d\alpha \ll H^3 P^{2+\varepsilon}.$$

Thus, by applying Hölder's inequality in combination with Hua's lemma (see Lemma 2.5 of [14]), we deduce that

$$\begin{aligned} T_2 &\ll P^{1+\varepsilon}Q^2 + \left(\int_0^1 |\Phi(\alpha)|^4 d\alpha \right)^{1/4} \left(\int_0^1 |g(\alpha)|^8 d\alpha \right)^{1/4} \left(\int_0^1 |g(\alpha)|^4 d\alpha \right)^{1/2} \\ &\ll P^{1+\varepsilon}Q^2 + P^\varepsilon(H^3P^2)^{1/4}(Q^5)^{1/4}(Q^2)^{1/2} \\ &\ll P^\varepsilon(PQ^2 + P^{-1}Q^{9/2}). \end{aligned}$$

This confirms the first conclusion of the lemma.

Suppose next that $P^{4/5} \leq Q \leq P$. In this situation, the argument of the lemma of [10] shows that when $\alpha \in \mathbb{R}$ and $a \in \mathbb{Z}$ and $q \in \mathbb{N}$ satisfy $|\alpha - a/q| \leq q^{-2}$ and $(a, q) = 1$, then

$$\Phi(\alpha) \ll P^\varepsilon(HPq^{-1/2} + HP^{1/2} + H^{1/2}q^{1/2}).$$

Thus, following the argument on pages 19 and 20 of [10], we see that

$$\begin{aligned} T_2 &\ll P^{1+\varepsilon}Q^2 + P^{1/2+\varepsilon}HQ^2 + P^\varepsilon \sum_{1 \leq q \leq P} (HPQq^{-5/6} + P^2q^{-1/2}) \\ &\ll P^{1+\varepsilon}Q^2 + P^{1/2+\varepsilon}HQ^2(P^{2/3}Q^{-1} + M^5P^{-1} + 1). \end{aligned}$$

When $P^{4/5} \leq Q \leq P$, we therefore conclude that

$$T_2 \ll P^{1+\varepsilon}Q^2 + P^{1/2+\varepsilon}HQ^2,$$

an estimate which yields the second conclusion of the lemma.

The final assertion of the lemma follows from the first when $Q \leq P^{4/5}$, and from the second when $P^{4/5} \leq Q \leq P^{5/6}$. \square

We finish this section by swiftly disposing of the mean value T_3 .

Lemma 2.4. *Suppose that $R \leq Q \leq P^{5/6}$. Then one has*

$$T_3 \ll P^{1+\varepsilon}QR.$$

Proof. Since $R \leq Q \leq P^{5/6}$, if we first apply Schwarz's inequality to (2.5), and then make use of the final estimate of Lemma 2.3, we obtain

$$\begin{aligned} T_3 &\leq \left(\int_0^1 |f(\alpha)^2 g(\alpha)^4| d\alpha \right)^{1/2} \left(\int_0^1 |f(\alpha)^2 h(\alpha)^4| d\alpha \right)^{1/2} \\ &\ll P^\varepsilon(PQ^2)^{1/2}(PR^2)^{1/2}. \end{aligned}$$

The desired conclusion follows. \square

3. AN AUXILIARY MINOR ARC ESTIMATE

An active ingredient in our argument is an auxiliary minor arc estimate derived by analytic differencing. This section is devoted to the proof of an estimate for a certain eighth moment of cubic exponential sums that has arisen in a weaker form in the earlier work of Vaughan [13]. We must first introduce

some notation. Let P be a large real number, and let Y be a real number with $P^{1/8} \leq Y \leq P^{1/7}$. Also, when X and Z are positive numbers, define

$$\mathcal{A}^*(X, Z) = \{n \in \mathbb{Z} \cap [1, X] : \varpi \text{ prime and } \varpi|n \Rightarrow \varpi \leq Z^\eta\},$$

and put $\mathcal{B}(X, Z) = \mathcal{A}^*(2X, Z) \setminus \mathcal{A}^*(X, Z)$. Note that $\mathcal{A}(X) = \mathcal{A}^*(X, X)$. Define the exponential sums $k_p(\alpha) = k_p(\alpha; Y)$ and $K(\alpha) = K(\alpha; Y)$ by

$$k_p(\alpha; Y) = \sum_{w \in \mathcal{B}(P/p, 2P/Y)} e(\alpha w^3) \quad \text{and} \quad K(\alpha; Y) = \sum_{Y < p \leq 2Y} k_p(p^3 \alpha; Y). \quad (3.1)$$

Also, write

$$f_p(\alpha) = \sum_{\substack{P < x \leq 2P \\ (x, p) = 1}} e(\alpha x^3) \quad \text{and} \quad l_p(\alpha) = \sum_{P/p < u \leq 2P/p} e(\alpha u^3). \quad (3.2)$$

We next introduce a set of major and minor arcs suitable for our analysis. When X is a real parameter with $1 \leq X \leq P^{3/2}$, we define

$$\mathfrak{M}(q, a; X) = \{\alpha \in [0, 1) : |q\alpha - a| \leq XP^{-3}\},$$

and then take $\mathfrak{M}(X)$ to be the union of the arcs $\mathfrak{M}(q, a; X)$ with $0 \leq a \leq q \leq X$ and $(a, q) = 1$. We then put $\mathfrak{m}(X) = [0, 1) \setminus \mathfrak{M}(X)$.

The key theorem of this section provides a bound for the eighth moment

$$\mathfrak{I}(Y) = \int_{\mathfrak{m}(PY^3)} |f(\alpha)^2 K(\alpha)^6| d\alpha. \quad (3.3)$$

Theorem 3.1. *Whenever $P^{1/8} \leq Y \leq P^{1/7}$, one has*

$$\mathfrak{I}(Y) \ll P^{19/4} Y^{-3/4} (P/Y)^{\varepsilon - \tau} + P^{9/2 + \varepsilon} Y.$$

We remark that Vaughan [13] has analysed the mean value (3.3) in the special case $Y = P^{1/8}$. In this restricted situation, the antepenultimate display of §5 of [13] supplies a bound similar to that given by Theorem 3.1, though weaker by a factor exceeding $Y^{1/2}$. The estimate supplied by our theorem matches in strength the bounds made available, by the interwoven arrangements of generating functions, applied in the arguments leading to the sharpest available estimates for the exceptional set in Waring's problem for sums of four cubes (see [4]). The latter arguments fail to capture the expected number of solutions, since the generating functions applied do not have full density, a deficiency that is absent from the bound summarised below in Corollary 3.2.

Proof. Our argument involves a careful consideration of the possible prime factors implicit in the generating functions $K(\alpha)$ that are common to the exponential sums $f(\alpha)$ lying within the mean value in question. It is convenient throughout to write $\mathfrak{m} = \mathfrak{m}(PY^3)$. Furthermore, within this proof, summations over the variable p will denote sums over prime numbers p with $p \equiv 2 \pmod{3}$ and $Y < p \leq 2Y$.

On recalling (3.2), we see that for any prime number p , one has

$$f(\alpha) = f_p(\alpha) + l_p(p^3 \alpha). \quad (3.4)$$

Consequently, it follows from (3.1) that

$$\begin{aligned} f(\alpha)^2 K(\alpha) &= \sum_p f(\alpha)^2 k_p(p^3 \alpha) \\ &\ll \sum_p (|f_p(\alpha)^2 k_p(p^3 \alpha)| + |l_p(p^3 \alpha)^2 k_p(p^3 \alpha)|). \end{aligned}$$

On substituting the latter relation into (3.3), we find that

$$\mathfrak{I}(Y) \ll \mathfrak{I}_1 + \mathfrak{I}_2, \quad (3.5)$$

where

$$\mathfrak{I}_1 = \int_{\mathfrak{m}} |K(\alpha)|^5 \sum_p |f_p(\alpha)^2 k_p(p^3 \alpha)| d\alpha \quad (3.6)$$

and

$$\mathfrak{I}_2 = \int_{\mathfrak{m}} |K(\alpha)|^5 \sum_p |l_p(p^3 \alpha)^2 k_p(p^3 \alpha)| d\alpha. \quad (3.7)$$

An application of Hölder's inequality reveals that

$$\sum_p |f_p(\alpha)^2 k_p(p^3 \alpha)| \leq \left(\sum_p |f_p(\alpha)^2 k_p(p^3 \alpha)^6| \right)^{1/6} \left(\sum_p |f_p(\alpha)|^2 \right)^{5/6}.$$

Applying Hölder's inequality a second time, we derive from (3.6) the bound

$$\mathfrak{I}_1 \leq \mathfrak{I}_3^{1/6} \mathfrak{I}_4^{5/6}, \quad (3.8)$$

where

$$\mathfrak{I}_3 = \sum_p \int_{\mathfrak{m}} |f_p(\alpha)^2 k_p(p^3 \alpha)^6| d\alpha \quad (3.9)$$

and

$$\mathfrak{I}_4 = \int_{\mathfrak{m}} |K(\alpha)|^6 \sum_p |f_p(\alpha)|^2 d\alpha.$$

We return to the consideration of \mathfrak{I}_3 later in the proof, for this is the central object of our attention. So far as \mathfrak{I}_4 is concerned, we may make use again of (3.4) to deduce that

$$\mathfrak{I}_4 \ll \mathfrak{I}_5 + \mathfrak{I}_6, \quad (3.10)$$

where

$$\mathfrak{I}_5 = \sum_p \int_{\mathfrak{m}} |f(\alpha)^2 K(\alpha)^6| d\alpha$$

and

$$\mathfrak{I}_6 = \int_{\mathfrak{m}} |K(\alpha)|^6 \sum_p |l_p(p^3 \alpha)|^2 d\alpha. \quad (3.11)$$

In view of (3.3), one has $\mathfrak{I}_5 \ll Y \mathfrak{I}(Y)$. In addition, when $Y < p \leq 2Y$, the discussion surrounding equation (34) of [13] supplies the estimate

$$\sup_{\alpha \in \mathfrak{m}} |l_p(p^3 \alpha)| \ll (P/p)^{3/4+\varepsilon}, \quad (3.12)$$

and, on considering the underlying diophantine equations, Lemma 2 of [5] delivers the bound

$$\int_0^1 |K(\alpha)|^6 d\alpha \ll P^{3+\varepsilon} Y^2. \quad (3.13)$$

We therefore deduce from (3.11) that

$$\mathfrak{T}_6 \ll P^{3/2+\varepsilon} Y^{-1/2} \int_0^1 |K(\alpha)|^6 d\alpha \ll P^{9/2+\varepsilon} Y^{3/2}.$$

Thus, on substituting this together with our earlier estimate for \mathfrak{T}_5 into (3.10), we obtain the upper bound

$$\mathfrak{T}_4 \ll Y(\mathfrak{T}(Y) + P^{9/2+\varepsilon} Y^{1/2}). \quad (3.14)$$

We turn our attention next to \mathfrak{T}_2 , first applying Cauchy's inequality to obtain

$$\sum_p |l_p(p^3\alpha)^2 k_p(p^3\alpha)| \leq \left(\sum_p |l_p(p^3\alpha)|^4 \right)^{1/2} \left(\sum_p |k_p(p^3\alpha)|^2 \right)^{1/2}.$$

Substituting into (3.7) and recalling (3.12), we discover that

$$\mathfrak{T}_2 \ll P^{3/2+\varepsilon} Y^{-1} \int_0^1 |K(\alpha)|^5 \left(\sum_p |k_p(p^3\alpha)|^2 \right)^{1/2} d\alpha.$$

An application of Hölder's inequality therefore reveals that

$$\mathfrak{T}_2 \ll P^{3/2+\varepsilon} Y^{-1} \left(\int_0^1 |K(\alpha)|^6 d\alpha \right)^{1/2} \mathfrak{T}_7^{1/2},$$

where

$$\mathfrak{T}_7 = \int_0^1 |K(\alpha)|^4 \sum_p |k_p(p^3\alpha)|^2 d\alpha.$$

On considering the underlying diophantine equations, one sees that

$$\int_0^1 |K(\alpha)|^4 \sum_p |k_p(p^3\alpha)|^2 d\alpha \ll \int_0^1 |K(\alpha)|^6 d\alpha,$$

and hence it follows from (3.13) that

$$\mathfrak{T}_2 \ll P^\varepsilon (P^{3/2} Y^{-1}) (P^3 Y^2) = P^{9/2+\varepsilon} Y. \quad (3.15)$$

We now substitute (3.8), (3.14) and (3.15) into (3.5) to obtain the upper bound

$$\mathfrak{T}(Y) \ll P^{9/2+\varepsilon} Y + (Y^5 \mathfrak{T}_3)^{1/6} \mathfrak{T}(Y)^{5/6} + (Y^5 \mathfrak{T}_3)^{1/6} (P^{9/2+\varepsilon} Y^{1/2})^{5/6}.$$

We therefore have

$$\begin{aligned} \mathfrak{T}(Y) &\ll P^{9/2+\varepsilon} Y + Y^5 \mathfrak{T}_3 + (Y^5 \mathfrak{T}_3)^{1/6} (P^{9/2+\varepsilon} Y^{1/2})^{5/6} \\ &\ll P^{9/2+\varepsilon} Y + Y^5 \mathfrak{T}_3. \end{aligned} \quad (3.16)$$

Write

$$k^*(\alpha) = \max_{Y < p \leq 2Y} |k_p(\alpha)|. \quad (3.17)$$

Then by applying Lemma 4 of [5], we deduce from (3.9) that

$$\mathfrak{I}_3 \ll P^{3/2+\varepsilon} Y^{-5/2} \int_0^1 k^*(\alpha)^6 d\alpha.$$

The Carleson-Hunt theorem (see Hunt [8], Theorem 1), in combination with (2.2) above, shows that

$$\int_0^1 k^*(\alpha)^6 d\alpha \ll \int_0^1 \left| \sum_{w \in \mathcal{A}(2P/Y)} e(\alpha w^3) \right|^6 d\alpha \ll (P/Y)^{13/4-\tau},$$

and thus we see that

$$\mathfrak{I}_3 \ll P^{19/4} Y^{-23/4} (P/Y)^{\varepsilon-\tau}.$$

The proof of Theorem 3.1 is completed by substituting this estimate into (3.16). \square

It is convenient to have available a variant of Theorem 3.1 that facilitates simplifications in associated major arc analyses. We first introduce some additional notation. Put $J = \lceil \frac{1}{2}\tau \log P \rceil$, and define the exponential sum

$$\tilde{K}(\alpha) = \sum_{j=1}^J K(\alpha; 2^{-j}Y), \tag{3.18}$$

and the mean value

$$\tilde{\mathfrak{I}}(Y) = \int_{\mathfrak{m}(PY^3)} |f(\alpha)^2 \tilde{K}(\alpha)^6| d\alpha. \tag{3.19}$$

Corollary 3.2. *Whenever $P^{1/8+\tau/2} \leq Y \leq P^{1/7}$, one has*

$$\tilde{\mathfrak{I}}(Y) \ll P^{19/4-\tau/2} Y^{-3/4} + P^{9/2+\varepsilon} Y.$$

Proof. An application of Hölder's inequality leads from (3.18) to the bound

$$\int_{\mathfrak{m}(PY^3)} |f(\alpha)^2 \tilde{K}(\alpha)^6| d\alpha \ll (\log P)^6 \max_{1 \leq j \leq J} \mathfrak{I}(2^{-j}Y).$$

The desired conclusion now follows from Theorem 3.1 with a modicum of computation. \square

4. THE APPLICATION OF THE CIRCLE METHOD

Having equipped ourselves with the tools required in our application of the Hardy-Littlewood method, our goal in this section is to engineer the framework required for the application of Bessel's inequality to the problem of estimating the exceptional set at hand. Let N be a large positive number, and write

$$P = (N/4)^{1/3}, \quad Q = P^{5/6}, \quad Y = P^{11/79} \quad \text{and} \quad L = (\log P)^{1/10}.$$

We consider a parameter θ with $0 \leq \theta \leq \frac{1}{3}$, write $\phi = 3\theta$, and fix $R = P^\phi$. In addition, we put $J = \lceil \frac{1}{2}\tau \log P \rceil$, as in the previous section. Define $\rho(n) = \rho_\theta(n)$ to be the number of integral representations of n in the form

$$n = x^3 + (pw)^3 + y^3 + z^3,$$

with

$$P < x \leq 2P, \quad Q < y \leq 2Q, \quad z \in \mathcal{A}(R),$$

$$2^{-j}Y < p \leq 2^{1-j}Y \quad \text{and} \quad w \in \mathcal{B}(P/p, 2^{1+j}P/Y) \quad (1 \leq j \leq J).$$

Our goal is to establish that, when $\frac{362}{869} \leq \phi \leq \frac{14}{33} - \frac{\tau}{6}$, then for almost all values of n with $N < n \leq 2N$, one has $\rho_\theta(n) \gg n^{\theta-1/18}$. Since $r_\theta(n) \geq \rho_\theta(n)$, the conclusion of Theorem 1.1 follows by summing over dyadic intervals.

Next, given a measurable set $\mathfrak{B} \subseteq [0, 1)$, we define

$$\rho(n; \mathfrak{B}) = \int_{\mathfrak{B}} f(\alpha) \tilde{K}(\alpha) g(\alpha) h(\alpha) e(-n\alpha) d\alpha. \quad (4.1)$$

By orthogonality, one then has $\rho_\theta(n) = \rho(n; [0, 1))$. We estimate the latter quantity by means of the circle method. Our argument involves two pruning steps, and we therefore introduce various classes of arcs to facilitate the analysis. First, when $a \in \mathbb{Z}$, $q \in \mathbb{N}$ and $(a, q) = 1$, we put

$$\mathfrak{P}(q, a) = \{\alpha \in [0, 1) : |\alpha - a/q| \leq LN^{-1}\}.$$

We then define \mathfrak{P} to be the union of the arcs $\mathfrak{P}(q, a)$ with $0 \leq a \leq q \leq L$ and $(a, q) = 1$, and write $\mathfrak{p} = [0, 1) \setminus \mathfrak{P}$. Next, in the notation introduced in the previous section prior to the statement of Theorem 3.1, when $1 \leq X \leq P^{3/2}$, we define $\mathfrak{K}(X) = \mathfrak{M}(2X) \setminus \mathfrak{M}(X)$. In addition, we write

$$\mathfrak{m} = \mathfrak{m}(PY^3), \quad \mathfrak{V} = \mathfrak{M}(PY^3) \setminus \mathfrak{M}(P^{6/5}) \quad \text{and} \quad \mathfrak{U} = \mathfrak{M}(P^{6/5}) \setminus \mathfrak{P}.$$

Finally, it is convenient for future reference to introduce the generating functions

$$S(q, a) = \sum_{r=1}^q e(ar^3/q) \quad \text{and} \quad v(\beta) = \int_P^{2P} e(\beta\gamma^3) d\gamma. \quad (4.2)$$

Lemma 4.1. *One has $\rho(n; \mathfrak{P}) \gg n^{\theta-1/18}$ for all integers n satisfying $N < n \leq 2N$, with at most $O(NL^{-1/16})$ possible exceptions.*

Proof. By Theorem 4.1 of [14], when $a \in \mathbb{Z}$, $q \in \mathbb{N}$ and $\beta \in \mathbb{R}$, one has

$$f(\beta + a/q) - q^{-1}S(q, a)v(\beta) \ll q^{1/2+\varepsilon}(1 + P^3|\beta|)^{1/2}. \quad (4.3)$$

Hence, when $\alpha \in \mathfrak{P}(q, a) \subseteq \mathfrak{P}$, one sees that

$$f(\alpha) - q^{-1}S(q, a)v(\alpha - a/q) \ll L^{1+\varepsilon}.$$

Also, on examining the Taylor expansion of $e(\beta\gamma^3)$, one finds in like manner that when $\alpha \in \mathfrak{P}(q, a) \subseteq \mathfrak{P}$, then

$$g(\alpha) - q^{-1}S(q, a)g(0) \ll LQ^4P^{-3} \ll Q^{1/2}.$$

Similarly, it follows from Lemma 8.5 of [15] that for $\alpha \in \mathfrak{P}(q, a) \subseteq \mathfrak{P}$, one has

$$h(\alpha) - q^{-1}S(q, a)h(0) \ll RL^{-5},$$

and that when $1 \leq j \leq J$ and $2^{-j}Y < p \leq 2^{1-j}Y$, there exists a positive number c , depending only on η , such that

$$k_p(p^3\alpha; 2^{-j}Y) - cq^{-1}S(q, ap^3) \int_{P/p}^{2P/p} e(p^3\gamma^3(\alpha - a/q)) d\gamma \ll Pp^{-1}L^{-5}.$$

We note that when $2^{-j}Y < p \leq Y$ and $q \leq L$, one has $p \nmid q$, and so one may apply a change of variables to show that $S(q, ap^3) = S(q, a)$. Following another change of variables, one sees that

$$\tilde{K}(\alpha) - \sum_{2^{-j}Y < p \leq Y} c(pq)^{-1}S(q, a)v(\alpha - a/q) \ll PL^{-5}.$$

The prime number theorem in arithmetic progressions implies that

$$\sum_{2^{-j}Y < p \leq Y} p^{-1} = \frac{1}{2} \log \left(\frac{\log Y}{\log(2^{-j}Y)} \right) + O \left(\frac{1}{\log Y} \right),$$

and thus we deduce that

$$\tilde{K}(\alpha) - Cq^{-1}S(q, a)v(\alpha - a/q) \ll PL^{-5},$$

where

$$C = \frac{c}{2} \log \left(\frac{22}{22 - (79 \log 2)\tau} \right) > 0.$$

Next, write

$$T(q, a) = q^{-4}S(q, a)^4 \quad \text{and} \quad u(\beta) = Cv(\beta)^2g(0)h(0). \quad (4.4)$$

Then, from the above approximations, one discerns that for $\alpha \in \mathfrak{P}(q, a) \subseteq \mathfrak{P}$, one has

$$f(\alpha)\tilde{K}(\alpha)g(\alpha)h(\alpha) - T(q, a)u(\alpha - a/q) \ll P^2QRL^{-5}.$$

Since the measure of \mathfrak{P} is $O(L^3N^{-1})$, from (4.1) we reach the formula

$$\rho(n; \mathfrak{P}) = \mathfrak{S}(n; L)\mathcal{J}(n; L) + O(P^2QRN^{-1}L^{-2}), \quad (4.5)$$

where

$$\mathfrak{S}(n; L) = \sum_{1 \leq q \leq L} A(q, n), \quad (4.6)$$

in which we have written

$$A(q, n) = \sum_{\substack{a=1 \\ (a,q)=1}}^q T(q, a)e(-na/q),$$

and

$$\mathcal{J}(n; L) = \int_{-L/N}^{L/N} u(\beta)e(-\beta n) d\beta.$$

The expression $\mathfrak{S}(n; L)$ is a partial sum of the familiar singular series

$$\mathfrak{S}(n) = \sum_{q=1}^{\infty} A(q, n) \quad (4.7)$$

associated with sums of four cubes. The standard theory of singular series establishes that the series $\mathfrak{S}(n)$ converges absolutely, and satisfies $1 \ll \mathfrak{S}(n) \ll (\log \log n)^4$ (see Theorem 4.3 of [14] and equation (1.3) of [9]). Moreover, on recalling the notation introduced prior to equation (2.13), we find from Lemmata 2.11 and 4.7 of [14] that $A(q, n) \ll q^{1/2+\varepsilon} \kappa(q)^4(q, n)$. We therefore deduce that

$$\begin{aligned} \sum_{N < n \leq 2N} |\mathfrak{S}(n) - \mathfrak{S}(n; L)| &\leq \sum_{N < n \leq 2N} \sum_{q=1}^{\infty} (q/L)^{1/8} |A(q, n)| \\ &\ll L^{-1/8} \sum_{q=1}^{\infty} q^{2/3} \kappa(q)^4 \sum_{\substack{d|q \\ N < n \leq 2N \\ (q, n) = d}} (q, n) \\ &\ll NL^{-1/8} \sum_{q=1}^{\infty} q^{2/3} \kappa(q)^4 d(q), \end{aligned}$$

where $d(q)$ denotes the number of distinct divisors of q . The final sum over q converges, since

$$\sum_{q=1}^{\infty} q^{2/3} \kappa(q)^4 d(q) = \prod_{\varpi \text{ prime}} (1 + 2\varpi^{-4/3} + O(\varpi^{-2})) \ll 1,$$

and hence the inequality $|\mathfrak{S}(n) - \mathfrak{S}(n; L)| > L^{-1/16}$ can hold for at most $O(NL^{-1/16})$ integers n with $N < n \leq 2N$. In particular, one may conclude that $|\mathfrak{S}(n; L)| \gg 1$ for all integers n satisfying $N < n \leq 2N$, with at most $O(NL^{-1/16})$ possible exceptions.

Integration by parts, meanwhile, confirms the estimate

$$v(\beta) \ll P(1 + P^3|\beta|)^{-1}, \quad (4.8)$$

and hence one has

$$u(\beta) \ll P^2QR(1 + P^3|\beta|)^{-2}. \quad (4.9)$$

It follows that

$$\mathcal{J}(n; L) - \int_{-\infty}^{\infty} u(\beta) e(-\beta n) d\beta \ll P^2QRN^{-1}L^{-1}.$$

The last integral here converges absolutely, in view of (4.9). It may therefore be evaluated by following a standard treatment, such as that described on pages 21 and 22 of [7]. The result is that when $N < n \leq 2N$, the integral is bounded below by $c_0 P^2QRN^{-1}$, where c_0 is a certain positive absolute constant. For the same values of n , it follows that

$$\mathcal{J}(n; L) \gg P^2QRN^{-1}.$$

On collecting these lower bounds within (4.5), we conclude that one has

$$\rho(n; \mathfrak{P}) \gg P^2QRN^{-1} \gg n^{\theta-1/18}$$

for all integers n satisfying $N < n \leq 2N$, with at most $O(NL^{-1/16})$ possible exceptions. This completes the proof of the lemma. \square

In §5 below, we show that when $\frac{362}{869} \leq \phi \leq \frac{14}{33} - \frac{\tau}{6}$, then

$$\sum_{N < n \leq 2N} |\rho(n; \mathfrak{p})|^2 \ll N^{2\theta+8/9} L^{-1/8}, \quad (4.10)$$

so that $|\rho(n; \mathfrak{p})| \ll n^{\theta-1/18} (\log n)^{-1/200}$ for almost all natural numbers n with $N < n \leq 2N$. Granted this conclusion, it follows from Lemma 4.1 that for almost all such n , one has

$$\rho_\theta(n) = \rho(n; \mathfrak{P}) + \rho(n; \mathfrak{p}) \gg n^{\theta-1/18}.$$

The conclusion of Theorem 1.1 follows on recalling that $r_\theta(n) \geq \rho_\theta(n)$, and then summing over dyadic intervals.

5. THE MINOR ARC CONTRIBUTION

We derive (4.10) by applying Bessel's inequality, though several pruning operations are required.

Lemma 5.1. *Provided that $\frac{362}{869} \leq \phi \leq \frac{14}{33} - \frac{\tau}{6}$, one has*

$$\sum_{N < n \leq 2N} |\rho(n; \mathfrak{m})|^2 \ll N^{2\theta+8/9} L^{-10}.$$

Proof. By Bessel's inequality, it follows from (4.1) that

$$\sum_{N < n \leq 2N} |\rho(n; \mathfrak{m})|^2 \leq \int_{\mathfrak{m}} |f(\alpha) \tilde{K}(\alpha) g(\alpha) h(\alpha)|^2 d\alpha.$$

An application of Hölder's inequality therefore yields the upper bound

$$\sum_{N < n \leq 2N} |\rho(n; \mathfrak{m})|^2 \leq T_1^{1/3} T_2^{1/3} \tilde{\mathfrak{I}}(Y)^{1/3},$$

where T_1 , T_2 and $\tilde{\mathfrak{I}}(Y)$ are respectively given by (2.3), (2.4) and (3.19). Hence, by appealing to Lemmata 2.2 and 2.3, and Corollary 3.2, we arrive at the estimate

$$\begin{aligned} \sum_{N < n \leq 2N} |\rho(n; \mathfrak{m})|^2 &\ll P^\varepsilon (PQR^{13/4-\tau})^{1/3} (PQ^2)^{1/3} (P^{19/4-\tau/2} Y^{-3/4})^{1/3} \\ &\ll P^{9/4-\tau/6+\varepsilon} QR^{13/12-\tau/3} Y^{-1/4}. \end{aligned}$$

A modest computation now reveals that the conclusion of the lemma holds provided that

$$P^{37/12} R^{13/12} Y^{-1/4} \leq P^{8/3} R^2,$$

as is guaranteed whenever $R \geq P^{5/11} Y^{-3/11}$. Consequently, whenever $\phi \geq \frac{5}{11} - \frac{3}{79} = \frac{362}{869}$, the conclusion of the lemma follows. \square

We now come to the first pruning step.

Lemma 5.2. *Provided that $\frac{362}{869} \leq \phi \leq \frac{14}{33} - \frac{\tau}{6}$, one has*

$$\sum_{N < n \leq 2N} |\rho(n; \mathfrak{B})|^2 \ll N^{2\theta+8/9} L^{-10}.$$

Proof. We begin by estimating the contribution arising from the set $\mathfrak{R}(X)$. By Bessel's inequality, it follows from (4.1) that when $1 \leq X \leq PY^3$, one has

$$\sum_{N < n \leq 2N} |\rho(n; \mathfrak{R}(X))|^2 \leq \mathcal{I}_0, \quad (5.1)$$

where

$$\mathcal{I}_0 = \int_{\mathfrak{R}(X)} |f(\alpha) \tilde{K}(\alpha) g(\alpha) h(\alpha)|^2 d\alpha. \quad (5.2)$$

When $X \geq P^{6/5}$, it is a consequence of (4.3), together with (4.8) and Theorem 4.2 of [14], that

$$\sup_{\alpha \in \mathfrak{R}(X)} |f(\alpha)| \ll PX^{-1/3} + X^{1/2+\varepsilon} \ll X^{1/2+\varepsilon}.$$

Under the same hypotheses on X , therefore, an application of Hölder's inequality leads from (5.2) to the estimate

$$\begin{aligned} \mathcal{I}_0 &\ll X^{1/6+\varepsilon} \int_{\mathfrak{R}(X)} |f(\alpha)|^{5/3} |\tilde{K}(\alpha) g(\alpha) h(\alpha)|^2 d\alpha \\ &\leq T_1^{1/3} T_2^{1/6} (X^{1/2+\varepsilon} \mathcal{I}_1)^{1/3} \left(\int_0^1 |\tilde{K}(\alpha)^2 g(\alpha)^4| d\alpha \right)^{1/6}, \end{aligned} \quad (5.3)$$

where T_1 and T_2 are given by (2.3) and (2.4), and

$$\mathcal{I}_1 = \int_{\mathfrak{R}(X)} |f(\alpha)^2 \tilde{K}(\alpha)^5| d\alpha. \quad (5.4)$$

But on considering the diophantine equation underlying (2.4), and noting (2.1), (3.1) and (3.18), we find that

$$T_2 \geq \int_0^1 |\tilde{K}(\alpha)^2 g(\alpha)^4| d\alpha,$$

and so (5.3) becomes

$$\mathcal{I}_0 \ll T_1^{1/3} T_2^{1/3} (X^{1/2+\varepsilon} \mathcal{I}_1)^{1/3}. \quad (5.5)$$

The expression \mathcal{I}_1 has been examined already in the course of the proof of Theorem 3 of [5], although in that treatment the focus is on the situation wherein $X = PY^3$. A careful examination of that argument reveals that whenever $P^{6/5} \leq X \leq PY^3$, one has the estimate

$$\int_{\mathfrak{R}(X)} |f(\alpha)^2 K(\alpha)^5| d\alpha \ll P^{4+\lambda} Y^{-1-\lambda} (PY^3/X)^{1/2}, \quad (5.6)$$

in which we have written $\lambda = \frac{3}{34} - \frac{\tau}{4}$. The validity of this claim requires a few words of justification. First, the estimates on pages 28 and 29 of [5] remain valid provided only that $X > 8Y^3(P/Y)^{3/4}$, as is guaranteed whenever $X \geq P^{6/5}$ and $Y \leq P^{1/7}$ (see the discussion prior to equation (5.10) of [5]). Thus the estimate (5.6) above follows from a satisfactory modification of the proof of Lemma 4 of [5], and in this proof the set \mathfrak{n} now becomes the set $\alpha \in [0, 1)$ with the property that whenever q is a natural number with $\|q\alpha\| \leq$

$XY^{-3}Q^{-3}$, then one has $q > XY^{-3}$. In this lemma we put $S(\alpha) = k^*(\alpha)^5$, with $k^*(\alpha)$ defined as in (3.17). Now, in the notation of [5], one finds on the top of page 27 that the estimate

$$\sup_{\alpha \in \mathfrak{n}} \left(\sum_{1 \leq h \leq H} |F(\alpha h, \gamma; h)|^2 \right) \ll HP^{1+\varepsilon}(PY^3/X)$$

holds uniformly in γ . Likewise, provided that $X \geq Y^6$, one finds that

$$\sup_{\alpha \in \mathfrak{n}} \left(\sum_{1 \leq h \leq H} |G_h(\alpha h^3, \pm \gamma h)|^2 \right) \ll P^\varepsilon HY.$$

Thus, on checking the argument on pages 155 and 156 of [11], one concludes from the argument of the proof of Lemma 4 together with §5 of [5] that

$$\int_{\mathfrak{R}(X)} |f(\alpha)^2 K(\alpha)^5| d\alpha \ll P^{3/2+\varepsilon} Y^{3/2} (PY^3/X)^{1/2} \int_0^1 k^*(\alpha)^5 d\alpha.$$

An application of the Carleson-Hunt theorem [8] in combination with Theorem 1.2 of [17] reveals that

$$\int_0^1 k^*(\alpha)^5 d\alpha \ll \int_0^1 \left| \sum_{w \in \mathcal{A}(2P/Y)} e(\alpha w^3) \right|^5 d\alpha \ll (P/Y)^{44/17-2\tau/7},$$

and the conclusion (5.6) follows at once.

An application of Hölder's inequality establishes that

$$|\tilde{K}(\alpha)|^5 \ll (\log P)^5 \max_{1 \leq j \leq J} |K(\alpha; 2^{-j}Y)|^5,$$

and so we deduce from (5.4) and (5.6) that

$$\begin{aligned} \mathcal{I}_1 &\ll (\log P)^5 \max_{1 \leq j \leq J} \int_{\mathfrak{R}(X)} |f(\alpha)^2 K(\alpha; 2^{-j}Y)^5| d\alpha \\ &\ll P^{4+\lambda+\varepsilon} Y^{-1-\lambda} (PY^3/X)^{1/2}. \end{aligned} \quad (5.7)$$

Substituting (5.7) into (5.5) along with the conclusions of Lemmata 2.2 and 2.3, we find that

$$\mathcal{I}_0 \ll P^\varepsilon (PQR^{13/4-\tau})^{1/3} (PQ^2)^{1/3} (P^{9/2+\lambda} Y^{1/2-\lambda})^{1/3}.$$

Therefore, provided that $P^{6/5} \leq X \leq PY^3$, we deduce that

$$\mathcal{I}_0 \ll P^{13/6+\lambda/3+\varepsilon} QR^{13/12-\tau/3} Y^{1/6-\lambda/3} \ll P^{3+\lambda/3} R^{13/12-\tau/4} Y^{1/6-\lambda/3}.$$

Since $Y = P^{11/79}$, we obtain $\mathcal{I}_0 \ll PQ^2 R^{2-\tau/4} \Delta$, where

$$\Delta = P^{37/102} R^{-11/12} Y^{7/51} = (P^{362/869} R^{-1})^{11/12}.$$

Thus, whenever $R \geq P^\phi$ and $P^{6/5} \leq X \leq PY^3$, one finds from (5.1) that

$$\sum_{N < n \leq 2N} |\rho(n; \mathfrak{R}(X))|^2 \ll N^{2\theta+8/9} R^{-\tau/4}.$$

The conclusion of the lemma now follows by summing over dyadic intervals covering the range $P^{6/5} \leq X \leq PY^3$ for the parameter X , and then recalling the definition of ϕ . \square

Lemma 5.3. *Provided that $\frac{362}{869} \leq \phi \leq \frac{14}{33} - \frac{\tau}{6}$, one has*

$$\sum_{N < n \leq 2N} |\rho(n; \mathfrak{U})|^2 \ll N^{2\theta+8/9} L^{-1/8}.$$

Proof. By Bessel's inequality, it follows from (4.1) that

$$\sum_{N < n \leq 2N} |\rho(n; \mathfrak{U})|^2 \leq \mathcal{J}_0, \quad (5.8)$$

where

$$\mathcal{J}_0 = \int_{\mathfrak{U}} |f(\alpha) \tilde{K}(\alpha) g(\alpha) h(\alpha)|^2 d\alpha.$$

We define the function $f^*(\alpha)$ for $\alpha \in [0, 1)$ by putting

$$f^*(\alpha) = q^{-1} S(q, a) v(\alpha - a/q), \quad (5.9)$$

when $\alpha \in \mathfrak{M}(q, a; P^{6/5}) \subseteq \mathfrak{M}(P^{6/5})$, and otherwise by taking $f^*(\alpha) = 0$. Referring once again to (4.3), and noting that $\mathfrak{U} \subseteq \mathfrak{M}(P^{6/5})$, we find that when $\alpha \in \mathfrak{U}$, one has

$$f(\alpha) - f^*(\alpha) \ll P^{3/5+\varepsilon},$$

whence

$$\mathcal{J}_0 \ll P^{6/5+\varepsilon} \mathcal{J}_1 + \mathcal{J}_2,$$

where

$$\mathcal{J}_1 = \int_0^1 |\tilde{K}(\alpha) g(\alpha) h(\alpha)|^2 d\alpha$$

and

$$\mathcal{J}_2 = \int_{\mathfrak{U}} |f^*(\alpha) \tilde{K}(\alpha) g(\alpha) h(\alpha)|^2 d\alpha. \quad (5.10)$$

But on considering the underlying diophantine equations, it follows from (2.5) that $\mathcal{J}_1 \leq T_3$, and hence Lemma 2.4 implies that

$$\mathcal{J}_0 \ll P^{11/5+\varepsilon} QR + \mathcal{J}_2. \quad (5.11)$$

Write

$$v_0(\beta) = \int_Q^{2Q} e(\beta\gamma^3) d\gamma,$$

and define the function $g^*(\alpha)$ for $\alpha \in [0, 1)$ by taking

$$g^*(\alpha) = q^{-1} S(q, a) v_0(\alpha - a/q),$$

when $\alpha \in \mathfrak{M}(q, a; P^{6/5}) \subseteq \mathfrak{M}(P^{6/5})$, and otherwise by setting $g^*(\alpha) = 0$. Then it follows from Theorem 4.1 of [14] that when $\alpha \in \mathfrak{M}(P^{6/5})$, one has

$$g(\alpha) - g^*(\alpha) \ll P^{3/5+\varepsilon}.$$

On making use of this estimate within (5.10), we see that

$$\mathcal{J}_2 \ll P^{6/5+\varepsilon} \mathcal{J}_3 + \mathcal{J}_4, \quad (5.12)$$

where

$$\mathcal{J}_3 = \int_{\mathfrak{U}} |f^*(\alpha) \tilde{K}(\alpha) h(\alpha)|^2 d\alpha \quad (5.13)$$

and

$$\mathcal{J}_4 = \int_{\mathfrak{U}} |f^*(\alpha)g^*(\alpha)\tilde{K}(\alpha)h(\alpha)|^2 d\alpha. \quad (5.14)$$

Next define $\Omega(\alpha)$ for $\alpha \in [0, 1)$ by taking

$$\Omega(\alpha) = (q + P^3|q\alpha - a|)^{-1},$$

when $\alpha \in \mathfrak{M}(q, a; P^{6/5}) \subseteq \mathfrak{M}(P^{6/5})$, and otherwise by putting $\Omega(\alpha) = 0$. Then an inspection of (5.9) leads from (4.8) and Theorem 4.2 of [14] to the bound

$$f^*(\alpha) \ll P\Omega(\alpha)^{1/3} \ll P^{6/5}\Omega(\alpha)^{1/2}.$$

On substituting this estimate into (5.13) and applying Lemma 2 of [2], we deduce that

$$\begin{aligned} \mathcal{J}_3 &\ll P^{12/5+\varepsilon} \int_{\mathfrak{M}(P^{6/5})} \Omega(\alpha)|\tilde{K}(\alpha)h(\alpha)|^2 d\alpha \\ &\ll P^{\varepsilon-3/5} \left(P^{6/5} \int_0^1 |\tilde{K}(\alpha)h(\alpha)|^2 d\alpha + P^2 R^2 \right). \end{aligned}$$

A diminishing ranges argument akin to that establishing Lemma 2.1 therefore shows that whenever $P^{1/5} \leq R \leq P^{2/3}$, one has

$$\mathcal{J}_3 \ll P^{\varepsilon-3/5}(P^{11/5}R + P^2R^2) \ll P^{7/5+\varepsilon}R^2. \quad (5.15)$$

Following the argument that led to the relation (2.14), one finds that when $\alpha \in \mathfrak{M}(q, a; P^{6/5}) \subseteq \mathfrak{M}(P^{6/5})$, one has

$$g^*(\alpha) \ll Qq^\varepsilon \kappa(q) \quad \text{and} \quad f^*(\alpha) \ll Pq^{1+\varepsilon} \kappa(q)\Omega(\alpha).$$

Consequently, under the same conditions on α , one has

$$f^*(\alpha)g^*(\alpha) \ll PQq^{1+\varepsilon}\kappa(q)^2\Omega(\alpha) \ll PQ\Omega(\alpha)^{1/2}.$$

In particular, whenever $\alpha \in \mathfrak{U}$ one has $f^*(\alpha)g^*(\alpha) \ll PQL^{-1/2}$. An application of Hölder's inequality therefore leads from (5.14) to the estimate

$$\mathcal{J}_4 \ll h(0)^2(PQL^{-1/2})^{1/4} \mathcal{J}_5^{1/4} \mathcal{J}_6^{3/4}, \quad (5.16)$$

where

$$\mathcal{J}_5 = \int_0^1 |\tilde{K}(\alpha)|^8 d\alpha \quad \text{and} \quad \mathcal{J}_6 = \int_{\mathfrak{U}} |f^*(\alpha)g^*(\alpha)|^{7/3} d\alpha.$$

From Theorem 2 of [11], one finds that $\mathcal{J}_5 \ll P^5$. Meanwhile, a direct computation reveals that

$$\begin{aligned} \mathcal{J}_6 &\ll (PQ)^{7/3} \left(\sum_{q=1}^{\infty} q^{1+\varepsilon} \kappa(q)^{14/3} \right) \int_{-\infty}^{\infty} (1 + P^3|\beta|)^{-7/3} d\beta \\ &\ll (PQ)^{7/3} P^{-3}. \end{aligned}$$

Thus, it follows from (5.16) that

$$\mathcal{J}_4 \ll R^2(PQL^{-1/2})^{1/4}(P^5)^{1/4}((PQ)^{7/3}P^{-3})^{3/4} \ll PQ^2R^2L^{-1/8}. \quad (5.17)$$

On combining (5.17) with (5.12) and (5.15), and then resubstituting into (5.11), we see that

$$\mathcal{J}_0 \ll P^{11/5+\varepsilon}QR + P^{13/5+\varepsilon}R^2 + PQ^2R^2L^{-1/8} \ll PQ^2R^2L^{-1/8},$$

and the conclusion of the lemma now follows from (5.8). \square

The estimate (4.10) is obtained by combining the conclusions of Lemmata 5.1, 5.2 and 5.3. We have $\mathfrak{p} \subseteq \mathfrak{m} \cup \mathfrak{A} \cup \mathfrak{B}$, and so

$$\begin{aligned} \sum_{N < n \leq 2N} |\rho(n; \mathfrak{p})|^2 &\ll \sum_{N < n \leq 2N} (|\rho(n; \mathfrak{m})|^2 + |\rho(n; \mathfrak{A})|^2 + |\rho(n; \mathfrak{B})|^2) \\ &\ll N^{2\theta+8/9}(L^{-10} + L^{-1/8}). \end{aligned}$$

In view of the concluding remarks of §4, the proof of Theorem 1.1 is now complete.

6. THE ASYMPTOTIC FORMULA FOR SUMS OF FOUR CUBES

Our objective in this section is the proof of Theorem 1.2. Experts will find the argument straightforward, though there are some technical irritations. We begin by adjusting some of our earlier notation in order to fit the circumstances at hand. Let N be a large positive number, and write $P = (N/4)^{1/3}$ and $L = (\log P)^{100}$. We consider a parameter θ with $0 \leq \theta < 1/3$, and take R to be a number with $N^\theta \leq R \leq (2N)^\theta$. Define $\sigma(n) = \sigma_\theta(n)$ to be the number of integral representations of n in the form

$$n = x_1^3 + x_2^3 + x_3^3 + y^3, \quad (6.1)$$

with $x_i \in \mathbb{N}$ ($i = 1, 2, 3$) and $1 \leq y \leq R$. Notice that when $N < n \leq 2N$, then given any representation of n in the shape (6.1), one has

$$1 \leq x_i \leq (2N)^{1/3} \quad (i = 1, 2, 3) \quad \text{and} \quad \max_{1 \leq i \leq 3} x_i > (N/4)^{1/3}.$$

Thus

$$1 \leq x_i \leq 2P \quad (i = 1, 2, 3) \quad \text{and} \quad \max_{1 \leq i \leq 3} x_i > P.$$

We define

$$F(\alpha) = \sum_{1 \leq x \leq 2P} e(\alpha x^3), \quad F_0(\alpha) = \sum_{1 \leq y \leq P} e(\alpha y^3),$$

and

$$G(\alpha) = \sum_{1 \leq z \leq R} e(\alpha z^3).$$

Then, given a measurable set $\mathfrak{B} \subseteq [0, 1)$, we define

$$\sigma(n; \mathfrak{B}) = \int_{\mathfrak{B}} (F(\alpha)^3 - F_0(\alpha)^3) G(\alpha) e(-n\alpha) d\alpha. \quad (6.2)$$

Notice that by orthogonality, one has $\sigma_\theta(n) = \sigma(n; [0, 1))$ whenever $N < n \leq 2N$. Next we define the set of arcs \mathfrak{B} as in §4, and take $\mathfrak{N} = \mathfrak{M}(P^{3/4})$ and $\mathfrak{n} = [0, 1) \setminus \mathfrak{N}$. Finally, we recall the familiar singular series $\mathfrak{S}(n)$ associated with sums of four cubes defined above in equation (4.7).

Lemma 6.1. *One has*

$$\sigma(n; \mathfrak{P}) = \Gamma\left(\frac{4}{3}\right)^3 \mathfrak{S}(n)R + O(RL^{-1/16})$$

for all integers n satisfying $N < n \leq 2N$, with at most $O(NL^{-1/16})$ possible exceptions.

Proof. Write

$$w_0(\beta) = \int_0^P e(\beta\gamma^3) d\gamma, \quad w_1(\beta) = \int_0^{2P} e(\beta\gamma^3) d\gamma, \quad w_2(\beta) = \int_0^R e(\beta\gamma^3) d\gamma.$$

Also, define the functions $F^*(\alpha)$, $F_0^*(\alpha)$ and $G^*(\alpha)$ for $\alpha \in [0, 1)$ by putting

$$F^*(\alpha) = q^{-1}S(q, a)w_1(\beta), \quad F_0^*(\alpha) = q^{-1}S(q, a)w_0(\beta)$$

and

$$G^*(\alpha) = q^{-1}S(q, a)w_2(\beta),$$

when $\alpha \in \mathfrak{P}(q, a) \subseteq \mathfrak{P}$, and otherwise set each function to be zero. Then as a consequence of Theorem 4.1 of [14], when $\alpha \in \mathfrak{P}$ one has

$$F(\alpha) - F^*(\alpha) \ll L^{1/2+\varepsilon}, \quad F_0(\alpha) - F_0^*(\alpha) \ll L^{1/2+\varepsilon},$$

and

$$G(\alpha) - G^*(\alpha) \ll L^{1/2+\varepsilon}.$$

Now define $T(q, a)$ as in (4.4), and put

$$W(\beta) = (w_1(\beta)^3 - w_0(\beta)^3)w_2(\beta).$$

Then we see that for $\alpha \in \mathfrak{P}(q, a) \subseteq \mathfrak{P}$, one has

$$(F(\alpha)^3 - F_0(\alpha)^3)G(\alpha) - T(q, a)W(\alpha - a/q) \ll P^3L^{1/2+\varepsilon}.$$

Since the measure of \mathfrak{P} is $O(L^3N^{-1})$, we deduce from (6.2) that

$$\sigma(n; \mathfrak{P}) - \mathfrak{S}(n; L)\mathcal{J}_0(n; L) \ll L^{7/2+\varepsilon}, \quad (6.3)$$

where $\mathfrak{S}(n; L)$ is defined as in (4.6), and

$$\mathcal{J}_0(n; L) = \int_{-L/N}^{L/N} W(\beta)e(-\beta n) d\beta.$$

The series $\mathfrak{S}(n; L)$ has already been considered during the course of the proof of Lemma 4.1. In particular, it follows that for all integers n with $N < n \leq 2N$, one has

$$|\mathfrak{S}(n; L) - \mathfrak{S}(n)| \leq L^{-1/16},$$

with at most $O(NL^{-1/16})$ possible exceptions. In addition, for all natural numbers n , one has $1 \ll \mathfrak{S}(n) \ll (\log \log n)^4$. Note that the former conclusion is robust to the adjustment in our definition of L . Next, recall the definition (4.2). Then we see that

$$\begin{aligned} W(\beta) &= ((v(\beta) + w_0(\beta))^3 - w_0(\beta)^3)w_2(\beta) \\ &= (v(\beta)^3 + 3v(\beta)^2w_0(\beta) + 3v(\beta)w_0(\beta)^2)w_2(\beta). \end{aligned}$$

Then by (4.8) and the bound $w_0(\beta) \ll P(1 + P^3|\beta|)^{-1/3}$ that follows from Theorem 7.3 of [14], we see that

$$W(\beta) \ll P^3 R(1 + P^3|\beta|)^{-5/3}.$$

Consequently, one has

$$\mathcal{J}_0(n; L) - \int_{-\infty}^{\infty} W(\beta)e(-\beta n) d\beta \ll P^3 RN^{-1}L^{-2/3}.$$

The last integral may be evaluated in a standard manner (see pages 21 and 22 of [7]). Thus we see that when $N < n \leq 2N$, one has

$$\mathcal{J}_0(n; L) = \Gamma(\frac{4}{3})^3 R + O(RL^{-2/3})$$

(compare the discussion of §4 of [18]). On substituting these estimates into (6.3), we find that

$$\sigma(n; \mathfrak{P}) = \Gamma(\frac{4}{3})^3 \mathfrak{S}(n)R + O(RL^{-1/16}),$$

for all integers n satisfying $N < n \leq 2N$, with at most $O(NL^{-1/16})$ possible exceptions. The conclusion of the lemma follows. \square

Lemma 6.2. *Provided that $\frac{1}{4} < \theta < \frac{1}{3}$, one has*

$$\sum_{N < n \leq 2N} |\sigma(n; \mathfrak{p})|^2 \ll NR^2 L^{\varepsilon-1/3}.$$

Proof. An application of Bessel's inequality leads from (6.2) to the upper bound

$$\begin{aligned} \sum_{N < n \leq 2N} |\sigma(n; \mathfrak{p})|^2 &\ll \sum_{N < n \leq 2N} |\sigma(n; \mathfrak{n})|^2 + \sum_{N < n \leq 2N} |\sigma(n; \mathfrak{n} \setminus \mathfrak{P})|^2 \\ &\leq \Xi(\mathfrak{n}) + \Xi(\mathfrak{n} \setminus \mathfrak{P}), \end{aligned} \quad (6.4)$$

where for a measurable set \mathfrak{B} , we write

$$\Xi(\mathfrak{B}) = \int_{\mathfrak{B}} |(F(\alpha)^3 - F_0(\alpha)^3)G(\alpha)|^2 d\alpha.$$

It follows from (2.1) that

$$\int_{\mathfrak{n}} |(F(\alpha)^3 - F_0(\alpha)^3)G(\alpha)|^2 d\alpha \ll \int_{\mathfrak{n}} |f(\alpha)G(\alpha)|^2 (|F(\alpha)|^4 + |F_0(\alpha)|^4) d\alpha,$$

and so an application of Hölder's inequality reveals that

$$\Xi(\mathfrak{n}) \ll \left(\sup_{\alpha \in \mathfrak{n}} |f(\alpha)| \right) (\mathcal{K}_1 + \mathcal{K}_2)^{1/2} \mathcal{K}_3^{1/2},$$

where

$$\mathcal{K}_1 = \int_0^1 |F(\alpha)|^8 d\alpha, \quad \mathcal{K}_2 = \int_0^1 |F_0(\alpha)|^8 d\alpha$$

and

$$\mathcal{K}_3 = \int_0^1 |f(\alpha)^2 G(\alpha)^4| d\alpha.$$

But a modified version of Weyl's inequality (see, for example, Lemma 1 of [11]) confirms that

$$\sup_{\alpha \in \mathfrak{n}} |f(\alpha)| \ll P^{3/4+\varepsilon}.$$

Thus, on recalling Lemma 2.3 and applying Hua's lemma (see, for example, Lemma 2.5 of [14]), one finds that

$$\begin{aligned} \Xi(\mathfrak{n}) &\ll P^{3/4+\varepsilon} (P^5)^{1/2} (PR^2 + P^{-1}R^{9/2})^{1/2} \\ &\ll P^{3+\varepsilon} R^2 (P^{3/4}R^{-1} + (R/P)^{1/4}). \end{aligned} \quad (6.5)$$

It remains to estimate the contribution arising from the set of arcs $\mathfrak{N} \setminus \mathfrak{P}$. Here one may appeal to standard major arc technology (see Lemma 5.1 of [12]) to show that

$$\begin{aligned} \Xi(\mathfrak{N} \setminus \mathfrak{P}) &\ll \sum_{1 \leq z_1, z_2 \leq R} \int_{\mathfrak{N} \setminus \mathfrak{P}} |F(\alpha)|^6 e(\alpha(z_1^3 - z_2^3)) d\alpha \\ &\quad + \sum_{1 \leq z_1, z_2 \leq R} \int_{\mathfrak{N} \setminus \mathfrak{P}} |F_0(\alpha)|^6 e(\alpha(z_1^3 - z_2^3)) d\alpha \\ &\ll P^3 R^2 L^{\varepsilon-1/3}. \end{aligned} \quad (6.6)$$

On substituting (6.5) and (6.6) into (6.4), we therefore deduce that

$$\sum_{N < n \leq 2N} |\sigma(n; \mathfrak{p})|^2 \ll P^3 R^2 L^{\varepsilon-1/3} + P^{3+\varepsilon} R^2 (P^{3/4}R^{-1} + (R/P)^{1/4}).$$

Consequently, when $\frac{1}{4} < \theta < \frac{1}{3}$, the conclusion of the lemma follows on recalling that $R = P^{3\theta}$. \square

We finish this section with the proof of Theorem 1.2. Observe first that when $\theta = \frac{1}{3}$, the desired conclusion is an immediate consequence of Theorem 3 of Vaughan [11], provided that one makes use of the refinement to be found in the main theorem of Boklan [1]. We assume henceforth, therefore, that $\frac{1}{4} < \theta < \frac{1}{3}$. When $N^\theta \leq R \leq (2N)^\theta$ with θ in the latter range, it follows from Lemma 6.2 that

$$\sum_{N < n \leq N + N/(\log N)^2} |\sigma(n; \mathfrak{p})|^2 \ll P^3 R^2 (\log N)^{-6}.$$

It follows, in particular, that $|\sigma(n; \mathfrak{p})| \ll R(\log N)^{-1}$ for all integers n with $N < n \leq N + N(\log N)^{-2}$, with at most $O(N(\log N)^{-4})$ exceptions. In combination with the conclusion of Lemma 6.1, this shows that

$$\sigma_\theta(n) = \sigma(n; [0, 1]) = \Gamma\left(\frac{4}{3}\right)^3 \mathfrak{S}(n)R + O(R(\log N)^{-1})$$

for all n with $N < n \leq N + N(\log N)^{-2}$, with at most $O(N(\log N)^{-4})$ exceptions. Given an interval of the latter type for n , one has

$$n^\theta = N^\theta + O(N^\theta(\log N)^{-2}).$$

There is therefore a positive constant A with the property that

$$N^\theta < n^\theta \leq N^\theta + AN^\theta(\log N)^{-2}.$$

Taking R to be first N^θ , and then $N^\theta + AN^\theta(\log N)^{-2}$, we see that

$$r_\theta(n) = \Gamma\left(\frac{4}{3}\right)^3 \mathfrak{S}(n) N^\theta + O(N^\theta (\log N)^{-1}),$$

whence

$$r_\theta(n) = \Gamma\left(\frac{4}{3}\right)^3 \mathfrak{S}(n) n^\theta + O(n^\theta (\log n)^{-1}),$$

for all n with $N < n \leq N + N(\log N)^{-2}$, with at most $O(N(\log N)^{-4})$ exceptions. On summing over the $O((\log N)^3)$ intervals of this type that cover $[1, 2N]$, we find that the total number of exceptions encountered is $O(N(\log N)^{-1})$, whence the conclusion of Theorem 1.2 follows also when $\frac{1}{4} < \theta < \frac{1}{3}$.

7. SUMS OF SIX CUBES AND A MINICUBE

Thus far, our conclusions have been of almost-all type. We now briefly discuss the proof of the following theorem.

Theorem 7.1. *All large natural numbers n are the sum of seven cubes of positive integers, one of which is no larger than $n^{43/168}$.*

We require a simple lemma.

Lemma 7.2. *Let $\mathcal{N}_\theta(X)$ denote the number of integers n with $1 \leq n \leq X$ that are the sum of three cubes of natural numbers, one of which is at most n^θ . Then whenever $0 \leq \theta \leq \frac{5}{18}$, one has*

$$\mathcal{N}_\theta(X) \gg X^{5/8 + \theta + \tau/9}.$$

Proof. Write $P = (X/20)^{1/3}$ and $R = (X/20)^\theta$. Also, let $\nu(n)$ denote the number of solutions of the equation

$$n = x_1^3 + x_2^3 + y^3,$$

with $x_i \in \mathcal{B}(P, P)$ and $1 \leq y \leq R$. Then by Cauchy's inequality, one has

$$\mathcal{N}_\theta(X) \geq \sum_{\substack{X/10 \leq n \leq X \\ \nu(n) \geq 1}} 1 \geq \left(\sum_{X/10 \leq n \leq X} \nu(n) \right)^2 \left(\sum_{1 \leq n \leq X} \nu(n)^2 \right)^{-1}. \quad (7.1)$$

Observe that

$$\sum_{X/10 \leq n \leq X} \nu(n) \gg P^2 R. \quad (7.2)$$

Also, in view of the underlying diophantine equation, one has

$$\sum_{1 \leq n \leq X} \nu(n)^2 \leq \int_0^1 |\mathcal{F}(\alpha)^4 G(\alpha)^2| d\alpha,$$

where we have written

$$\mathcal{F}(\alpha) = \sum_{x \in \mathcal{B}(P, P)} e(\alpha x^3).$$

By Schwarz's inequality, we obtain

$$\int_0^1 |\mathcal{F}(\alpha)^4 G(\alpha)^2| d\alpha \leq \left(\int_0^1 |\mathcal{F}(\alpha)|^6 d\alpha \right)^{1/2} \left(\int_0^1 |\mathcal{F}(\alpha)^2 G(\alpha)^4| d\alpha \right)^{1/2}.$$

The first integral may be estimated via (2.2), and the second by means of Lemma 2.3. Thus we deduce that when $\theta \leq \frac{5}{18}$, one has

$$\sum_{1 \leq n \leq X} \nu(n)^2 \ll (P^{13/4-\tau})^{1/2} (P^{1+\varepsilon} R^2)^{1/2}. \quad (7.3)$$

Finally, on substituting (7.2) and (7.3) into (7.1), we conclude that

$$\mathcal{N}_\theta(X) \gg (P^2 R)^2 (P^{17/8-\tau/3} R)^{-1} \gg P^{15/8+\tau/3} R,$$

thereby completing the proof of the lemma. \square

Next, let X be a sufficiently large positive number, and consider an integer n with $X \leq n \leq 2X$. By Lemma 7.2, at least $X^{5/8+\theta+\tau/9}$ of the integers m with $1 \leq m \leq X$ are the sum of three cubes of natural numbers, one of which is at most $m^\theta \leq n^\theta$. But all the integers $n - m$, with $1 \leq m \leq X$, are the sum of four cubes of natural numbers, with at most $O(X^{37/42})$ exceptions (see Theorem 1.3 of [17]). Thus, provided that $X^{5/8+\theta+\tau/9} > X^{37/42}$, then for at least one value of m with $1 \leq m \leq X$, one finds that m is the sum of three cubes of natural numbers, one at most n^θ , and $n - m$ is the sum of four positive integral cubes, whence n is the sum of six positive integral cubes and a minicube at most n^θ . The conclusion of Theorem 7.1 follows on observing that the above condition is satisfied whenever $\theta \geq \frac{43}{168}$.

REFERENCES

- [1] K. D. Boklan, *A reduction technique in Waring's problem, I*, Acta Arith. **65** (1993), 147–161.
- [2] J. Brüdern, *A problem in additive number theory*, Math. Proc. Cambridge Philos. Soc. **103** (1988), 27–33.
- [3] J. Brüdern, *Sums of four cubes*, Monatsh. Math. **107** (1989), 179–188.
- [4] J. Brüdern, *On Waring's problem for cubes*, Math. Proc. Cambridge Philos. Soc. **109** (1991), 229–256.
- [5] J. Brüdern and T. D. Wooley, *On Waring's problem: three cubes and a sixth power*, Nagoya Math. J. **163** (2001), 13–53.
- [6] H. Davenport, *On Waring's problem for cubes*, Acta Math. **71** (1939), 123–143.
- [7] H. Davenport, *Analytic methods for Diophantine equations and Diophantine inequalities*, Second edition, Cambridge University Press, Cambridge, 2005.
- [8] R. A. Hunt, *On the convergence of Fourier series*, Proceedings of the conference on orthogonal expansions and their continuous analogues (Edwardsville, Ill., 1967), Southern Illinois Univ. Press, Carbondale, Ill., pp. 235–255, 1968.
- [9] K. Kawada, *On the sum of four cubes*, Mathematika **43** (1996), 323–348.
- [10] R. C. Vaughan, *Sums of three cubes*, Bull. London Math. Soc. **17** (1985), 17–20.
- [11] R. C. Vaughan, *On Waring's problem for cubes*, J. Reine Angew. Math. **365** (1986), 122–170.
- [12] R. C. Vaughan, *A new iterative method in Waring's problem*, Acta Math. **162** (1989), 1–71.

- [13] R. C. Vaughan, *On Waring's problem for cubes II*, J. London Math. Soc. (2) **39** (1989), 205–218.
- [14] R. C. Vaughan, *The Hardy-Littlewood method*, second edition, Cambridge University Press, Cambridge, 1997.
- [15] T. D. Wooley, *On simultaneous additive equations, II*, J. Reine Angew. Math. **419** (1991), 141–198.
- [16] T. D. Wooley, *Breaking classical convexity in Waring's problem: sums of cubes and quasi-diagonal behaviour*, Invent. Math. **122** (1995), 421–451.
- [17] T. D. Wooley, *Sums of three cubes*, Mathematika **47** (2000), 53–61.
- [18] T. D. Wooley, *A light-weight version of Waring's problem*, J. Austral. Math. Soc. Ser. A **76** (2004), 303–316.

JB: INSTITUT FÜR ALGEBRA UND ZAHLENTHEORIE, UNIVERSITÄT STUTTGART, D-70511 STUTTGART, GERMANY

E-mail address: `bruedern@mathematik.uni-stuttgart.de`

TDW: SCHOOL OF MATHEMATICS, UNIVERSITY OF BRISTOL, UNIVERSITY WALK, CLIFTON, BRISTOL BS8 1TW, UNITED KINGDOM

E-mail address: `matdw@bristol.ac.uk`