On a Waring–Goldbach-type problem for fourth powers

Xiumin Ren and Kai-Man Tsang

Department of Mathematics, The University of Hong Kong, Pokfulam, Hong Kong

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Abstract

In this paper, we prove that every sufficiently large positive integer satisfying some necessary congruence conditions can be represented by the sum of a fourth power of integer and twelve fourth powers of prime numbers.

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Keywords: Waring–Goldbach problem; Circle method

1. Statement of the result

One of the problems of the Waring–Goldbach type is to find the least positive integer \( s \) such that every sufficiently large integer satisfying some necessary congruence conditions can be expressed by the sum of \( s \) fourth powers of primes. The expected value of \( s \) is 5, but this is far from reach by techniques developed so far. The present machinery in the circle method has been able to establish \( s = 14 \) which is due to Kawada and Wooley [7]. Precisely, they have proved that for all sufficiently

\*Corresponding author.

E-mail addresses: xmren@maths.hku.hk (X. Ren), kmtsang@maths.hku.hk (K.-M. Tsang).

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large integers \( n \equiv 14 \pmod{240} \), the equation
\[
  n = p_1^4 + p_2^4 + \cdots + p_{14}^4
\]
is solvable in primes \( p_j \).

On the other hand, concerning the corresponding Waring’s problem, Thanigasalam [11] has proved that
\[
  n = m_1^4 + m_2^4 + \cdots + m_{13}^4
\]
is solvable for every sufficiently large integer \( n \equiv r \pmod{16} \) where \( 1 \leq r \leq 13 \). Here \( m_j \) are positive integers. The number of variables 13 has been reduced to 12 by Vaughan [13]. Kawada and Wooley [6] can further reduce 12 to 11 except for \( r \equiv 11 \pmod{16} \). In this paper, we consider the expression
\[
  n = m^4 + p_1^4 + p_2^4 + \cdots + p_{12}^4,
\]
where \( m \) is a natural number and \( p_j \) are primes. Our result is the following.

**Theorem 1.** Eq. (1.1) is solvable for all sufficiently large integers \( n \) subject to
\[
  n \equiv a \pmod{240} \quad \text{for any} \quad a \in \mathcal{A},
\]
where
\[
\mathcal{A} = \{12, 13, 28, 93, 108, 157, 172, 237\}.
\]

**Notation.** As usual, \( \varphi(n) \) and \( A(n) \) stand for the function of Euler and von Mangoldt, respectively, and \( d(n) \) is the divisor function. We use \( \chi \pmod{q} \) and \( \chi^0 \pmod{q} \) to denote a Dirichlet character and the principal character modulo \( q \), and \( L(s, \chi) \) is the Dirichlet \( L \)-function. In our context, the letter \( N \) stands for a large positive integer, and \( L = \log N \). The symbol \( r \sim R \) means \( R \leq r \leq 2R \). The letters \( \varepsilon \) and \( A \) denote positive constants which are arbitrarily small and arbitrarily large, respectively. We use \( c_j \) to denote an absolute positive constant. The letter \( c \) denotes an unspecified positive constant which is not necessarily the same at each occurrence.

### 2. Outline of the method

Following [7], we introduce some notations. Let \( \lambda_0 = \frac{13}{16} \) and
\[
  \lambda_1 = \lambda_2 = 1, \quad \lambda_3 = \lambda_4 = \lambda_0, \quad \lambda_5 = \lambda_6 = \lambda_0^2,
\]
(2.1)
\[
\lambda_7 = \lambda_8 = 91\lambda_9^2/111, \quad \lambda_9 = \cdots = \lambda_{12} = 78\lambda_9^2/111, \quad (2.2)
\]
\[
\mu = (1 + \lambda_1 + \lambda_2 + \cdots + \lambda_{12})/4 = 2.22\ldots, \quad (2.3)
\]
\[
U = N^{1/4}/2, \quad U_i = U^{\lambda_i}, \quad i = 1, 2, \ldots, 12. \quad (2.4)
\]

In order to apply the circle method, we set
\[
P = U^{2/5}, \quad Q = NP^{-1}. \quad (2.5)
\]

Then by Dirichlet’s Lemma on rational approximations for each \(a \in [1/Q, 1 + 1/Q]\), there are coprime integers \(a, q\) satisfying \(1 \leq a \leq q \leq Q\) and
\[
a = a/q + \lambda, \quad |\lambda| \leq 1/qQ. \quad (2.6)
\]

We denote by \(\mathcal{M}(q,a)\) the set of all \(a\) satisfying (2.6). These intervals all lie in \([1/Q, 1 + 1/Q]\) and for \(q \leq P\) they are mutually disjoint, since \(2P \leq Q\). Let the major arcs \(\mathcal{M}\) and the minor arcs \(m\) be defined as follows:
\[
\mathcal{M} = \bigcup_{q \leq P} \bigcup_{a=1}^{q} \mathcal{M}(q,a), \quad m = [1/Q, 1 + 1/Q]\setminus \mathcal{M}.
\]

For \(W > 0\), we define
\[
S(z, W) = \sum_{m \sim W} A(m)e(m^4z), \quad \text{and} \quad T(z, W) = \sum_{m \sim W} e(m^4z), \quad (2.7)
\]
where \(e(z) = e^{2\pi iz}\). Let
\[
R(n) = \sum_{n = m_1^4 + m_2^4 + \cdots + m_{12}^4, m \sim U, m_i \sim U_i} A(m_1) \cdots A(m_{12}),
\]
which is the number of weighted representations of (1.1). Then we have
\[
R(n) = \int_{1/Q}^{1+1/Q} \left\{ \prod_{i=1}^{12} S(z, U_i) \right\} T(z, U)e(-nz) \, dz = \int_{\mathfrak{M}} + \int_{m}. \quad (2.8)
\]

To handle the integral on the major arcs, we need the following.

**Theorem 2.** For all \(n\) with \(N/2 < n \leq N\), we have
\[
\int_{\mathfrak{M}} \left\{ \prod_{i=1}^{12} S(z, U_i) \right\} T(z, U)e(-nz) \, dz = \mathfrak{S}(n)\mathfrak{S}(n) + O(N^{\mu-1}L^{-A}). \quad (2.9)
\]

Here \(\mathfrak{S}(n)\) is the singular series defined in (4.1) which satisfies
\[
1 \ll \mathfrak{S}(n) \ll 1 \quad (2.10)
\]
for $n$ satisfying (1.2); while $\mathcal{Z}(n)$ is defined by (4.10) and satisfies
\[ N^{\mu-1} \leq \mathcal{Z}(n) \leq N^{\mu-1}. \tag{2.11} \]

**Proof of Theorem 1.** We first establish the following estimate on the minor arcs.
\[
\left\lvert \int_m \left( \prod_{i=1}^{12} S(\alpha, U_i) \right) T(\alpha, U)e(-n\alpha) \, d\alpha \right\rvert \leq N^{\mu-1.01}. \tag{2.12}
\]

For $\alpha = a/q + \lambda \in m$, we have $P < q \leq Q$ and $|\lambda| \leq 1/qQ$. If $q > U$, then it follows from Weyl's inequality [14, Lemma 2.4] that $|T(\alpha, U)| \leq U^{7/8+\varepsilon}$. If $P < q \leq U$, we apply Lemmas 6.1–6.3 in [14], to get
\[
|T(\alpha, U)| \leq \frac{q^{-1/4}U}{1 + |\lambda|N} + q^{1/2+\varepsilon} \leq UP^{-1/4} + U^{1/2+\varepsilon} \leq U^{9/10}.
\]
Thus we can conclude that
\[
\max_{\alpha \in m} |T(\alpha, U)| \leq U^{9/10}.
\]
On the other hand, a slight modification of Theorem 3 for $j = 1$ in Thanigasalam [11] (or [7, Lemma 4.3]) reveals that
\[
\int_0^1 \left| \prod_{i=1}^{12} S(\alpha, U_i) \right| \, d\alpha \leq (U_1U_2\cdots U_{12})^{1/2} U^\varepsilon. \tag{2.13}
\]
Therefore
\[
\left\lvert \int_m \left( \prod_{i=1}^{12} S(\alpha, U_i) \right) T(\alpha, U)e(-n\alpha) \, d\alpha \right\rvert \\
\leq \max_{\alpha \in m} |T(\alpha, U)| \int_0^1 \left| \prod_{i=1}^{12} S(\alpha, U_i) \right| \, d\alpha \\
\leq U^{9/10+\varepsilon}(U_1U_2\cdots U_{12})^{1/2} \leq N^{\mu-1.01},
\]
by (2.1)–(2.4). This proves (2.12) which in combination with Theorem 2 and (2.8) gives
\[
R(n) = \mathcal{Z}(n)\mathcal{Z}(n) + O(N^{\mu-1}L^{-A}).
\]
Theorem 1 now follows by summing over dyadic intervals. \(\square\)

The following sections will be devoted to the proof of Theorem 2.
3. An explicit expression

In this section, we will establish in Lemma 3.1 an explicit expression for the left-hand side of (2.9). For \( \chi \mod q \), we define

\[
C(\chi, a) = \sum_{m=1}^{q} \bar{\chi}(m) e\left(\frac{am^4}{q}\right) \quad \text{and} \quad C(q, a) = C(\chi^0, a).
\]  

Then Vinogradov’s bound gives [15, Chapter VI, problem 14]

\[
|C(\chi, a)| \leq 2q^{1/2}d(q)^2.
\]  

For \( W > 0 \) and \( \alpha = a/q + \lambda \) with \( (a, q) = 1 \), we have

\[
S(\alpha, W) = \sum_{h=1}^{q} e\left(\frac{ah^4}{q}\right) \sum_{\chi \mod q, \chi(h) = 1} \sum_{m \sim W} A(m) e(\lambda m^4) + O(L^2).
\]

Introducing Dirichlet characters to the above sum over \( m \), one can rewrite \( S(\alpha, W) \) as

\[
\frac{C(q, a)}{\varphi(q)} \sum_{m \sim W} e(\lambda m^4) + \sum_{\chi \mod q} \frac{C(\chi, a)}{\varphi(q)} \sum_{m \sim W} (A(m) \chi(m) - \delta_\chi) e(\lambda m^4) + O(L^2).
\]

Here and throughout, \( \delta_\chi = 1 \) or 0 according as \( \chi \) is the principal character or not.

By Lemma 4.8 in [12], one has, for \( 0 < W \leq U \) and \( \alpha = a/q + \lambda \) subject to (2.6),

\[
\sum_{m \sim W} e(\lambda m^4) = \int_{W}^{2W} e(\lambda u^4) \, du + O(1).
\]

Thus if we denote by \( \Phi(\lambda, W) \) the above integral and write

\[
\Psi(\chi, \lambda, W) = \sum_{m \sim W} (A(m) \chi(m) - \delta_\chi) e(\lambda m^4),
\]

then

\[
S(\alpha, W) = S_1(\lambda, W) + S_2(\lambda, W) + O(L^2),
\]

where

\[
S_1(\lambda, W) = \frac{C(q, a)}{\varphi(q)} \Phi(\lambda, W), \quad S_2(\lambda, W) = \sum_{\chi \mod q} \frac{C(\chi, a)}{\varphi(q)} \Psi(\chi, \lambda, W).
\]

For \( T(\alpha, U) \), we apply Theorem 4.1 in [14] to get

\[
T(\alpha, U) = T(\lambda) + O(q^{1/2+\epsilon}),
\]
where

\[ T(\lambda) = \frac{S^*(q, a)}{q} \Phi(\lambda, U) \quad \text{with} \quad S^*(q, a) = \sum_{m=1}^{q} e\left( \frac{am^4}{q} \right). \]  

(3.5)

Let \( A(\lambda) \) be defined by

\[ \prod_{i=1}^{12} S(\alpha, U_i) = \prod_{i=1}^{12} S_1(\lambda, U_i) + A(\lambda), \]  

(3.6)

and let

\[ I = \sum_{q \leq P} \sum_{a=1}^{q} e\left( -\frac{an}{q} \right) \int_{-1/qQ}^{1/qQ} \left\{ \prod_{i=1}^{12} S_1(\lambda, U_i) \right\} T(\lambda)e(-n\lambda) \, d\lambda, \]  

(3.7)

\[ J = \sum_{q \leq P} \sum_{a=1}^{q} e\left( -\frac{an}{q} \right) \int_{-1/qQ}^{1/qQ} A(\lambda)T(\lambda)e(-n\lambda) \, d\lambda. \]  

(3.8)

Then we have

\[ \int_{\mathbb{R}} \left\{ \prod_{i=1}^{12} S(\alpha, U_i) \right\} T(\alpha, U)e(-n\alpha) \, d\alpha = I + J + O\left\{ P^{1/2+\epsilon} \int_{0}^{1} \left| \prod_{i=1}^{12} S(\alpha, U_i) \right| \, d\alpha \right\}, \]

where, by (2.13) and (2.1)–(2.5), the above \( O \)-term is

\[ \ll U^{1/5+\epsilon}(U_1 U_2 \cdots U_{12})^{1/2} \ll N^{n-1}L^{-A}. \]

Therefore we have proved the following.

**Lemma 3.1.** For all \( n \) with \( N/2 < n \leq N \), we have

\[ \int_{\mathbb{R}} \left\{ \prod_{i=1}^{12} S(\alpha, U_i) \right\} T(\alpha, U)e(-n\alpha) \, d\alpha = I + J + O(N^{n-1}L^{-A}). \]

In the following sections, we will prove that \( I \) produces the main term, while \( J \) contributes to the error term.
4. Estimation of $I$

Let $C(q,a)$ and $S^*(q,a)$ be defined by (3.1) and (3.5), respectively. We define

$$B(n,q) = \sum_{a=1 \atop (a,q)=1}^{q} e\left(-\frac{an}{q}\right) C^{12}(q,a) S^*(q,a),$$

and write

$$A(n,q) = \frac{B(n,q)}{n^\delta(q)}, \quad \Xi(n) = \sum_{q=1}^{\infty} A(n,q). \quad (4.1)$$

**Lemma 4.1.** The singular series $\Xi(n)$ is absolutely convergent and satisfies (2.10).

**Proof.** By (3.2) and the well-known bound $|S^*(q,a)| \ll q^{3/4+\varepsilon}$, one easily obtains

$$|A(n,q)| \ll q^{-21/4+\varepsilon}. \quad (4.2)$$

Therefore the singular series is absolutely convergent and satisfies the second inequality in (2.10). Moreover we have

$$\sum_{q \leq P} A(n,q) = \Xi(n) + O(P^{-17/4+\varepsilon}). \quad (4.3)$$

To prove the first inequality in (2.10), we first note that $A(n,q)$ is multiplicative with respect to $q$. We next prove that

$$A(n,p^t) = 0 \quad \text{for} \quad t \geq \varkappa,$$

where

$$\varkappa = \begin{cases} 2 & \text{if} \quad p \geq 3, \\ 5 & \text{if} \quad p = 2. \end{cases}$$

Actually, when $(a,p) = 1$ and $i \geq 2$, we have

$$C(p^i,a) = \sum_{m=1 \atop (m,p)=1}^{p^i} e\left(\frac{am^n}{p^i}\right) = \sum_{k=0}^{p^i-1} \sum_{m=1 \atop (m,p)=1}^{p^i-1} e\left(\frac{a(kp^n+m^4)}{p^i}\right)$$

$$= \sum_{k=0}^{p^i-1} \sum_{m=1 \atop (m,p)=1}^{p^i-1} e\left(\frac{4akm^n+p^i+am^4}{p^i}\right) = \sum_{m=1 \atop (m,p)=1}^{p^i-1} e\left(\frac{am^4}{p^i}\right) \sum_{k=0}^{p^i-1} e\left(\frac{4ak}{p}\right). \quad (4.5)$$
When $p \geq 3$, the inner sum is 0, and hence $A(n, p^i) = 0$. When $p = 2$ and $i \geq 5$, it follows from (4.5) that

$$C(2^i, a) = 2 \sum_{m=1}^{2^{i-1}} e\left(\frac{am^4}{2^i}\right) = 2 \sum_{k=0}^{2^{i-1}-1} \sum_{m=1}^{2^{i-3}} e\left(\frac{a(k2^{i-3} + m)^4}{2^i}\right)$$

$$= 4 \sum_{m=1}^{2^{i-3}} e\left(\frac{am^4}{2^i}\right) \sum_{k=0}^{1} e\left(\frac{ak}{2}\right) = 0.$$

Thus $A(n, 2^i) = 0$ for $i \geq 5$. This proves (4.4).

By (4.4) and the multiplicativity of $A(n, q)$, we can now write

$$\Xi(n) = (1 + A(n, 2) + A(n, 2^2) + A(n, 2^3) + A(n, 2^4)) \prod_{p \geq 2} (1 + A(n, p)). \quad (4.6)$$

Since $S^*(p, a) = C(p, a) + 1$ and $|C(p, a)| \leq 8p^{1/2}$, by (3.2), we have

$$|A(n, p)| \leq \frac{8^{13}p^{11/2} + 8^{12}p^5}{(p - 1)^{11}} \leq p^{-2}, \text{ when } p \geq c_1,$$

where $c_1$ is some positive constant. Hence

$$\prod_{p > c_1} (1 + A(n, p)) \geq c_2 > 0. \quad (4.7)$$

On the other hand, we have

$$1 + A(n, 2) + A(n, 2^2) + A(n, 2^3) + A(n, 2^4) = \frac{M(2^4, n)}{2^{36}},$$

and for $p > 2$,

$$1 + A(n, p) = \frac{M(p, n)}{(p - 1)^{12}}.$$

Here $M(p^i, n)$ is the number of solutions of the congruence

$$m_1^4 + m_2^4 + m_3^4 + \cdots + m_{12}^4 = n \pmod{p^i}$$

subject to

$$1 \leq m \leq p^i, \quad 1 \leq m_i < p^i \quad \text{with} \quad p \nmid m_i, \quad i = 1, 2, \ldots, 12.$$
By Lemma 8.8 in [3], we deduce that \( M(p, n) > 0 \) for all \( n \) and \( p \geq 7 \), and therefore
\[
\prod_{7 \leq p \leq c_1} (1 + A(n, p)) \geq c_3 > 0. \tag{4.8}
\]
Moreover, a direct investigation reveals that \( M(2^4, n) > 0 \) for \( n \equiv 12, 13(\text{mod } 16); M(3, n) > 0 \) for \( n \equiv 0, 1(\text{mod } 3) \) and \( M(5, n) > 0 \) for \( n \equiv \pm 2(\text{mod } 5) \). These estimates together with (4.6)–(4.8) prove that for \( n \) satisfying (1.2), \( \Xi(n) \geq c_4 > 0 \). Lemma 4.1 is thus established.

**Lemma 4.2.** Let \( I \) be defined by (3.7). Then for all \( n \in [N/2, N] \) subject to (1.2), we have
\[
I = \Xi(n) \mathfrak{I}(n) + O(N^{\mu - 1} L^{-4}),
\]
where \( \mathfrak{I}(n) \) is defined by (4.10) and satisfies (2.11).

**Proof.** By definition we have
\[
I = \sum_{q \leq P} A(n, q) \int_{-1/qQ}^{1/qQ} \left\{ \prod_{i=1}^{12} \Phi(\lambda, U_i) \right\} \Phi(\lambda, U) e(-n\lambda) \, d\lambda. \tag{4.9}
\]
Let
\[
\mathfrak{I}(n) = \int_{-\infty}^{\infty} \left\{ \prod_{i=1}^{12} \Phi(\lambda, U_i) \right\} \Phi(\lambda, U) e(-n\lambda) \, d\lambda. \tag{4.10}
\]
On using the elementary estimate
\[
|\Phi(\lambda, W)| \leq \min \left( W, \frac{1}{|\lambda| W^3} \right), \tag{4.11}
\]
one easily obtains
\[
\left\{ \prod_{k=1}^{12} \Phi(\lambda, U_i) \right\} \Phi(\lambda, U) \leq \frac{U^3 U_3 \cdots U_{12}}{(1 + |\lambda| N)^3} \leq \frac{N^{\mu}}{(1 + |\lambda| N)^3}. \tag{4.12}
\]
It therefore follows that
\[
\int_{-1/qQ}^{1/qQ} \left\{ \prod_{k=1}^{12} \Phi(\lambda, U_i) \right\} |\Phi(\lambda, U)| d\lambda \leq N^{\mu} \int_{-1/qQ}^{1/qQ} \frac{d\lambda}{(1 + |\lambda| N)^3} \leq N^{\mu - 1} (qQ/N)^2.
\]
Thus
\[
\int_{-1/qQ}^{1/qQ} \left\{ \prod_{k=1}^{12} \Phi(\lambda, U_i) \right\} \Phi(\lambda, U) e(-n\lambda) \, d\lambda = \mathfrak{I}(n) + O(N^{\mu - 1} P^{-2} q^2).
\]
Putting this in (4.9) and then making use of (4.3) and (4.2), we get

\[ I = \mathfrak{N}(n) \sum_{q \equiv p} A(n, q) + O\left( N^{\mu-1} P^{-2} \sum_{q \equiv p} q^2 |A(n, q)| \right) \]

\[ = \mathfrak{N}(n) \mathfrak{X}(n) + O(N^{\mu-1} P^{-2}), \]

subject to the validity of (2.11). Now it remains to check (2.11) of which the second inequality is an immediate derivation of (4.12). To prove the first inequality, we apply Fourier’s integral formula to get

\[ \mathfrak{N}(n) = \frac{1}{4\pi^3} \int_{D} u_1^{-3/4} u_2^{-3/4} \cdots u_{12}^{-3/4} du_1 du_2 \cdots du_{12}, \]

where \( u = n - u_1 - \cdots - u_{12} \), and \( D \) is the set of all vectors \((u_1, u_2, \ldots, u_{12})\) subject to

\[ U_i^4 < u_i \leq (2U_i)^4, \quad \text{and} \quad U^4 < u < (2U)^4. \]

Let \( D^* \) be the set of those vectors \((u_1, u_2, \ldots, u_{12})\) such that

\[ U_i^4 < u_i \leq (3U_i/2)^4 \quad \text{for} \quad i = 1, 2, \ldots, 12. \]

Then it is easy to check that \( U^4 < u < (2U)^4 \) holds for \((u_1, u_2, \ldots, u_{12}) \in D^* \). This means that \( D^* \) is a nonempty subset of \( D \), and hence

\[ \mathfrak{N}(n) \geq \int_{D^*} u_1^{-3/4} u_2^{-3/4} \cdots u_{12}^{-3/4} du_1 du_2 \cdots du_{12} \]

\[ \geq U^{-3} U_1 U_2 \cdots U_{12} \geq N^{\mu-1}. \]

This proves (2.11), and hence finishes the proof of Lemma 4.2. \( \square \)

5. Estimation of \( J \)

**Lemma 5.1.** Let \( J \) be as defined in (3.8). Then we have

\[ J \leq N^{\mu-1} L^{-A}. \]

To prove Lemma 5.1, we need the following lemma whose proof will be given in the next section.
Lemma 5.2. Let \( W \geq 1, \ R \geq 1 \) and \( 1 < q \leq W^d \) with \( d \geq 1 \). Then for \( k \geq 1 \) and \( \lambda \in \mathbb{R} \) subject to \( |\lambda| W^k \leq R \), we have

\[
\sum_{\chi \mod q} \left| \sum_{m \sim W} A(m) \chi(m) e(\lambda m^k) \right| \ll \{(R + (WR)^{1/2})q + W^{4/5}q^{1/2} + W\} L^c. \tag{5.1}
\]

Proof of Lemma 5.1. In view of (3.6) and (3.8), we see that \( J \) comprises \( 3^{12} - 1 \) terms of the form

\[
\sum_{q \leq p} \sum_{a=1}^{q} e\left( -\frac{an}{q} \right) \int_{-1/qQ}^{1/qQ} \prod_{i=1}^{12} E(\lambda, U_i) \left\{ T(\lambda)e(-n\lambda) \right\} d\lambda,
\]

where \( E(\lambda, U_i) = S_1(\lambda, U_i), S_2(\lambda, U_i) \) or \( L^2 \) with the exception that \( E(\lambda, U_i) = S_1(\lambda, U_i) \) holds for all \( i = 1, 2, \ldots, 12 \). Here \( S_1(\lambda, U_i), S_2(\lambda, U_i) \) are defined by (3.4). On using (3.2), we see that

\[
E(\lambda, U_i) \ll q^{-1/2 + \varepsilon} H(\lambda, U_i),
\]

where \( H(\lambda, U_i) \) represents any one of the following three expressions:

\[
|\Phi(\lambda, U_i)|, \sum_{\chi \mod q} |\Psi(\chi, \lambda, U_i)|, \ \ q^{1/2} L^2.
\]

Using the well-known bound \( S^* (q,a) \ll q^{3/4 + \varepsilon} \) in (3.5), we also see that

\[
|T(\lambda)| \ll q^{-1/4 + \varepsilon} |\Phi(\lambda, U)|.
\]

Therefore we get

\[
J \ll \sum_{q \leq p} q^{-21/4 + \varepsilon} \max_{|\lambda| \leq 1/qQ} \left\{ \prod_{i=1}^{12} H(\lambda, U_i) \right\} \int_{-1/qQ}^{1/qQ} |\Phi(\lambda, U)| d\lambda,
\]

where \( H(\lambda, U_i) \neq |\Phi(\lambda, U_i)| \) happens for at least one of \( i = 1, 2, \ldots, 12 \). Without loss of generality, we assume \( H(\lambda, U_2) \neq |\Phi(\lambda, U_2)| \).

By (4.11) one easily obtains

\[
\int_{-1/qQ}^{1/qQ} |\Phi(\lambda, U)| d\lambda \ll U^{-3} L.
\]
and hence
\[ J \ll U^{-3} L \sum_{q \leq P} q^{-21/4+\varepsilon} \max_{|\lambda| \leq 1/qQ} \left\{ \prod_{i=1}^{12} H(\lambda_i, U_i) \right\} \]
\[ =: U^{-3} L (J_1 + J_2). \]  
(5.2)

Here \( J_1 \) and \( J_2 \) represent sums over \( q \leq L^B \) and \( L^B < q \leq P \), respectively, with \( B = 4A \). So to prove Lemma 5.1, we only need to prove that
\[ J_1, J_2 \ll U_1 U_2 \cdots U_{12} L^{-A}. \]

One notes that for \( |\lambda| \leq 1/qQ \),
\[ |\lambda| U_i^4 \ll P/q \quad \text{for } i = 1, 2; \quad \text{and} \quad |\lambda| U_i^4 \ll 1, \quad \text{for } i = 3, 4, \ldots, 12. \]

Therefore it follows by trivial estimates and Lemma 5.2 that for \( q \leq P = U^{2/5} \),
\[ H(\lambda, U_1), H(\lambda, U_2) \ll \{(UPq)^{1/2} + U^{4/5} q^{1/2} + U\} L^c \ll UL^c, \]  
(5.3)

and
\[ H(\lambda, U_i) \ll \left\{ q U_i^{1/2} + q^{1/2} U_i^{4/5} + U_i \right\} L^c \quad \text{for } i = 3, 4, \ldots, 12. \]  
(5.4)

Thus we have
\[ J_2 \ll U_1 U_2 \cdots U_{12} L^c \sum_{L^B < q \leq P} q^{-21/4+\varepsilon} \prod_{i=3}^{12} \left( q U_i^{-1/2} + q^{1/2} U_i^{-5/5} + 1 \right). \]

Let
\[ \mu_3 = \mu_4 = (1 - \lambda_0)/2, \quad \mu_i = 1 - 5\lambda_i/4 \quad \text{for } i \geq 5, \]
where \( \lambda_i \) are defined by (2.1) and (2.2). Here \( \mu_i \) are so chosen that for \( 1 < q \leq P \),
\[ q^{-\mu_i} \left( q U_i^{-1/2} + q^{1/2} U_i^{-5/5} + 1 \right) \ll 1 \quad \text{for } i = 3, 4, \ldots, 12. \]

Write
\[ \mu^* = 21/4 - (\mu_3 + \cdots + \mu_{12}) = 2.38 \ldots. \]

Then
\[ J_2 \ll U_1 U_2 \cdots U_{12} L^c \sum_{L^B < q \leq P} q^{-\mu^*+\varepsilon} \ll U_1 U_2 \cdots U_{12} L^{-A}. \]  
(5.5)
Now we turn to $J_1$. For $q \leq L^B$, we see from (5.3) and (5.4) that $H(\lambda, U_i) \ll U_i L^c$ for $i = 1, 3, 4, \ldots, 12$. Hence

$$J_1 \ll U_1 U_3 \cdots U_{12} L^c \sum_{q \leq L^B} q^{-21/4+\epsilon} \max_{|\lambda| \leq 1/q} H(\lambda, U_2),$$

(5.6)

where $H(\lambda, U_2) = \sum_{\chi \mod q} |\Psi(\chi, \lambda, U_2)|$ or $q^{1/2} L^2$, by assumption. The desired assertion is obvious if $H(\lambda, U_2) = q^{1/2} L^2$. Otherwise we recall the explicit formula [1, Section 17, (9)–(10); Section 19, (4)–(9)]:

$$\sum_{m \leq x} A(m) \chi(m) = \delta_\chi x - \sum_{\rho \leq T} \frac{x^\rho}{\rho} + O\left(\frac{x(\log qxT)^2}{T}\right),$$

where $2 < T \leq x$ is a parameter and $\rho = \beta + iy$ is a typical nontrivial zero of the Dirichlet L-function $L(s, \chi)$. Let $T = PL^B$. Then by integrating by parts,

$$\Psi(\chi, \lambda, U_2) = \int_{U_2}^{2U_2} e(\lambda u^4) du \sum_{m \leq u} (A(m) \chi(m) - \delta_\chi)$$

$$= -\sum_{\rho \leq PL^B} \int_{U_2}^{2U_2} u^{\rho-1} e(\lambda u^4) du + O(U_2 P^{-1} L^{2-B} (1 + |\lambda| U_2^4))$$

$$\ll \sum_{\rho \leq PL^B} U_2^\beta + U_2 q^{-1} L^{2-B}.$$

Thus we get

$$H(\lambda, U_2) \ll U_2 \sum_{\chi \mod q} \sum_{|\lambda| \leq PL^B} U_2^{\beta-1} + U_2 L^{2-B}.$$

By Satz VIII.6.2 of Prachar [10] and Siegel’s theorem [1, Section 21], there exists a positive constant $c_5$ such that for $q \leq L^B$, $\prod_{\chi \mod q} L(s, \chi)$ is zero-free in the region

$$\sigma \geq 1 - c_5/\max\{\log q, \log^{4/5} x\}, \quad |\lambda| \leq x.$$

Let $\eta(N) = c_5 \log^{-4/5} N$. By integrating by parts, and then making use of the following well-known zero-density estimates (see for example [4, (1.1); 5, Theorem 1])

$$\sum_{\chi \mod q} N(\sigma, T, \chi) \ll (qT)^{(12/5+\epsilon)(1-\sigma)}, \quad 1/2 \leq \sigma \leq 1,$$
we have for \( q \leq L^B \),
\[
H(\lambda, U_2) \leq U_2 \max_{1/2 \leq \sigma \leq 1 - \eta(N)} (PL^B)^{(12/5+\varepsilon)(1-\sigma)} U_2^{-1} + U_2 L^{-2A}
\]
\[
\leq U_2 \max_{1/2 \leq \sigma \leq 1 - \eta(N)} U_2^{(2-1)/30} + U_2 L^{-2A}
\]
\[
\leq U_2 \exp(-c_6 L^{1/5}) + U_2 L^{-2A} \ll U_2 L^{-2A}.
\]
This together with (5.6) prove
\[
J_1 \ll U_1 U_2 \cdots U_{12} L^{-A}.
\]
With this, Lemma 5.1 follows from (5.2) and (5.5).

6. Proof of Lemma 5.2

Let \( M \geq 1 \) be a real number. For \( j = 1, \ldots, 10 \), let \( M_j \) be positive integers such that
\[
2^{-10} M \leq M_1 \cdots M_{10} \leq 2M, \quad \text{and} \quad 2M_6, \ldots, 2M_{10} \leq (2M)^{1/5}. \tag{6.1}
\]
For a positive integer \( m \), let
\[
a_j(m) = \begin{cases} 
\log m & \text{if } j = 1, \\
1 & \text{if } j = 2, \ldots, 5, \\
\mu(m) & \text{if } j = 6, \ldots, 10. 
\end{cases} \tag{6.2}
\]
We define the following functions of a complex variable \( s \):
\[
f_j(s, \chi) = \sum_{m \sim M_j} \frac{a_j(m) \chi(m)}{m^s}, \quad F(s, \chi) = f_1(s, \chi) \cdots f_{10}(s, \chi). \tag{6.3}
\]
To prove Lemma 5.2, we need the following mean value estimate for \( F(1/2 + it, \chi) \).

Lemma 6.1. Let \( d \geq 1 \) and \( g \geq 1 \). For \( 2 \leq T \leq M^g \) and \( 1 < q \leq M^d \), we have
\[
\sum_{\chi \bmod q} \int_T^{T} |F(1/2 + it, \chi)| dt \ll \{qT + (qT)^{1/2 M^{3/10} + M^{1/2}}\} L^c. \tag{6.4}
\]
To prove Lemma 6.1, we quote the following two well-known results (see for example [9, Theorems 2.5 and 3.17]).
Lemma 6.2. Let \( q \geq 1, \ T \geq 1, \ M_0 \geq 1 \) and \( D \geq 1 \). Let \( a_m \) be complex numbers. Then we have
\[
\sum_{\chi \mod q} \left| \sum_{m=M_0}^{M_0+D} \frac{a_m \chi(m)}{m^\sigma} \right|^2 dt \ll \sum_{m=M_0}^{M_0+D} (qT+m)|a_m|^2.
\]

Lemma 6.3. Let \( a_0 = 5 \) and \( a_1 = 9 \). Then for \( q \geq 2, \ T \geq 2 \) and \( v = 0, 1 \), we have
\[
\sum_{\chi \mod q} \int_{-T}^T \left| L^{(v)}(1/2 + it, \chi) \right|^4 dt \ll qT \log^4(qT).
\]

Proposition 6.4. If there exist \( M_i \) and \( M_j \) with \( 1 \leq i < j \leq 5 \) such that \( M_i M_j > M^{2/5} \), then (6.4) is true.

Proof. Without loss of generality, we may suppose that \( i = 1 \) and \( j = 2 \). Using Perron’s summation formula [12, Lemma 3.12] and then shifting the path of integration to the left, we get for \( \chi \neq \chi_0 \)
\[
f_1(1/2 + it, \chi) = -\frac{1}{2\pi i} \int_{1/2+1/L+iT_0}^{1/2+1/L-iT_0} L'(1/2 + it + w, \chi) \frac{(2M_1)^w - M_1^w}{w} dw + O(L^2)
\]
\[
= -\frac{1}{2\pi i} \left\{ \int_{1/2+1/L-iT_0}^{-iT_0} + \int_{iT_0}^{1/2+1/L+iT_0} + \int_{iT_0}^{-iT_0} \right\} + O(L^2),
\]
where \( T_0 = M^{d+\theta} \). One notes that the function \( (2M_1)^w - M_1^w \) has a removable singularity at \( w = 0 \). Thus, on the above vertical segment from \(-iT_0\) to \( iT_0\), we have
\[
\frac{(2M_1)^w - M_1^w}{iw} \ll \frac{1}{1 + |v|}.
\]
On using the well-known bounds (see for example [8, pp. 271, Exercise 6 and pp. 269, (13)]: For \( q \geq 1, \ \chi \neq \chi_0 \) and \( v \geq 0 \),
\[
L^{(v)}(\sigma + it, \chi) \ll \log^{(v+1)}(q(|t| + 2)) \max \left\{ 1, q^{(1-\sigma)/2}|t|^{1-\sigma} \right\}, \quad \sigma > 0,
\]
we see that the contribution from the two horizontal segments is
\[
\ll L^2 \max_{0 \leq u \leq 1/2+1/L} q^{(1-(1/2+u))/2} (T_0 + |t|^{1-(1/2+u)} M_1^u / T_0 \ll L^2 q^{1/4} T_0^{1/2} \ll 1,
\]

since \( q \leq M^d \leq T_0 \). Therefore we get

\[
 f_1(1/2 + it, \chi) \ll \int_{-T_0}^{T_0} |L'(1/2 + it + iv, \chi)| \frac{dv}{1 + |v|} + L^2,
\]

and by Hölder’s inequality,

\[
 \sum_{\chi \mod q} \int_{-T}^{T} |f_1(1/2 + it, \chi)|^4 dt \\
 \ll L^3 \sum_{\chi \mod q} \int_{-T}^{T} \int_{-T_0}^{T_0} |L'(1/2 + it + iv, \chi)|^4 \frac{dv dt}{1 + |v|} + O(qTL^8). \tag{6.5}
\]

Write \( \int_{-T_0}^{T_0} = \int_{|v| \leq 2T} + \int_{2T < |v| \leq T_0} \). Then the first term in (6.5) splits into two quantities, which we denote by \( \Sigma_1 \) and \( \Sigma_2 \), respectively. By Lemma 6.3, we have

\[
 \Sigma_1 \ll L^3 \sum_{\chi \mod q} \int_{-2T}^{2T} \frac{dv}{1 + |v|} \int_{-T}^{T} |L'(1/2 + iw, \chi)|^4 dw \\
 \ll L^4 \sum_{\chi \mod q} \int_{-3T}^{3T} |L'(1/2 + iw, \chi)|^4 dw \ll qTL^{13}.
\]

As regards \( \Sigma_2 \), let \( v = w - t \). Note that \( 2T \leq |w - t| \leq T_0 \) and \( |t| \leq T \) imply \( |w - t| \geq |w|/2 \) and \( T \leq |w| \leq 2T_0 \). Therefore

\[
 \Sigma_2 \ll TL^3 \sum_{\chi \mod q} \int_{-T}^{T} |L'(1/2 + iw, \chi)|^4 \frac{dw}{1 + |w|} \\
 \ll TL^4 \max_{T \leq X \leq T_0} \frac{1}{X} \sum_{\chi \mod q} \int_{-X}^{X} |L'(1/2 + iw, \chi)|^4 dw \ll qTL^{13},
\]

by Lemma 6.3. Collecting these estimates, we get

\[
 \sum_{\chi \mod q} \int_{-T}^{T} |f_1(1/2 + it, \chi)|^4 dt \ll qTL^{13}. \tag{6.6}
\]

A similar argument also leads to

\[
 \sum_{\chi \mod q} \int_{-T}^{T} |f_2(1/2 + it, \chi)|^4 dt \ll qTL^{9}. \tag{6.7}
\]
On the other hand, we have
\[
\prod_{j=3}^{10} f_j(1/2 + it, \chi) = \sum_{M_3 \cdots M_{10} < m \leq 2^8 M_3 \cdots M_{10}} \frac{b(m) \chi(m)}{m^{1/2 + it}},
\]
where \(|b(m)| \leq d_8(m)\). Thus by Lemma 6.2,
\[
\sum_{\chi \mod q \atop \chi \neq \chi_0} \left| \int_{-T}^{T} \prod_{j=3}^{10} f_j(1/2 + it, \chi) \, dt \right|^2 \leq \sum_{M_3 \cdots M_{10} < m \leq 2^8 M_3 \cdots M_{10}} (qT + m) \frac{d_8^2(m)}{m} \leq (qT + M^{3/5})L^c, \tag{6.8}
\]
since \(M_3 \cdots M_{10} \ll M/(M_1M_2) \ll M^{3/5}\). Writing
\[
F(1/2 + it, \chi) = f_1(1/2 + it, \chi)f_2(1/2 + it, \chi) \prod_{j=3}^{10} f_j(1/2 + it, \chi),
\]
then by Hölder’s inequality and (6.6)–(6.8), we get
\[
\sum_{\chi \mod q \atop \chi \neq \chi_0} \int_{-T}^{T} |F(1/2 + it, \chi)| \, dt \leq \left\{ \prod_{j=1}^{2} \left( \sum_{\chi \mod q \atop \chi \neq \chi_0} \left| \int_{-T}^{T} f_j(1/2 + it, \chi) \, dt \right|^4 \right)^{1/4} \right\} \left\{ \sum_{\chi \mod q \atop \chi \neq \chi_0} \int_{-T}^{T} \prod_{j=3}^{10} f_j(1/2 + it, \chi) \, dt \right\}^{1/2} \leq (qT)^{1/2}(qT + M^{3/5})^{1/2}L^c \ll (qT + (qT)^{1/2}M^{3/10})L^c.
\]
This proves Proposition 6.4.

Proposition 6.5. If there is a partition \(\{J_1, J_2\}\) of the set \(\{1, \ldots, 10\}\) such that
\[
\prod_{j \in J_1} M_j + \prod_{j \in J_2} M_j \ll M^{3/5},
\]
then (6.4) is true.

Proof. For \(v = 1, 2\), define
\[
F_v(s, \chi) := \prod_{j \in J_v} f_j(s, \chi) = \sum_{n \leq N_v} \frac{b_v(n)\chi(n)}{n^s},
\]
where \( N_v = \prod_{j \in J_v} (2M_j) \) and \( b_v(n) \ll Ld_1(n) \). By Lemma 6.2, we have
\[
\sum_{\chi \mod q} \int_T^{2T} |F_1(1/2 + it, \chi)|^2 dT \ll \sum_{n \leq N_1} (qT + n) \frac{|b_1(n)|^2}{n} \ll (qT + N_1) L^c,
\]
and similarly
\[
\sum_{\chi \mod q} \int_T^{2T} |F_2(1/2 + it, \chi)|^2 dT \ll (qT + N_2) L^c.
\]
Write \( F(s, \chi) = F_1(s, \chi)F_2(s, \chi) \). Then by Cauchy-schwarz’s inequality we get
\[
\sum_{\chi \mod q} \int_T^{2T} |F(1/2 + it, \chi)| dT \ll (qT + N_1)^{1/2}(qT + N_2)^{1/2} L^c
\]
\[
\ll (qT + (qT)^{1/2} M^{3/10} + M^{1/2}) L^c,
\]
since \( N_1 + N_2 \ll M^{3/5} \), and \( N_1N_2 \ll M \). This proves Proposition 6.5. \( \square \)

**Proof of Lemma 6.1.** In view of Proposition 6.4, we may assume that \( M_iM_j \ll M^{2/5} \) for all \( i,j \) with \( 1 \leq i < j \leq 5 \). It follows that there is at most one \( M_j \) with \( 1 \leq j \leq 5 \) such that \( M_j > M^{1/5} \). Without loss of generality, we can suppose this exceptional \( M_j \) is \( M_1 \), so we have \( M_j \ll M^{1/5} \) for \( j = 2, \ldots, 5 \), and also for \( j = 6, \ldots, 10 \), by assumption. Let \( l \) be the integer with \( 2 \leq l < 8 \) such that
\[
M_1 \cdots M_l \ll M^{2/5}, \quad \text{but} \quad M_1 \cdots M_{l+1} > M^{2/5}.
\]
Let \( J_1 = \{1, 2, \ldots, l + 1\} \) and \( J_2 = \{l + 2, \ldots, 10\} \). Write \( N_1 = M_1 \cdots M_{l+1} \) and \( N_2 = M_{l+2} \cdots M_{10} \). Then we have
\[
M^{2/5} \ll N_1 \ll M^{2/5} M_{l+1} \ll M^{2/5} M^{1/5} \ll M^{3/5}, \quad \text{and} \quad N_2 \ll M/N_1 \ll M^{3/5}.
\]
This proves \( N_1 + N_2 \ll M^{3/5} \), i.e. the assumption of Proposition 6.5 is satisfied. Lemma 6.1 thus follows. \( \square \)

**Proof of Lemma 5.2.** For \( W > 0 \), one has
\[
\sum_{\chi \mod q} \left| \sum_{m \sim W} A(m) \chi(m)e(\lambda m^k) \right| = \left| \sum_{m \sim W} A(m)e(\lambda m^k) \right| + \left| \sum_{\chi \mod q} \sum_{m \sim W} A(m) \chi(m)e(\lambda m^k) \right|. \quad (6.9)
\]
Obviously the first term is bounded by \( W \). By integrating by parts, we have
\[
\sum_{m \sim W} A(m) \chi(m) e(\lambda m^k) = \int_W^{2W} e(\lambda u^k) d \sum_{W < n \leq u} A(m) \chi(m).
\]

Now we apply Heath–Brown’s identity [2, Lemma 1] for \( k = 5 \) which states that for \( m \ll 2W \),
\[
A(m) = \sum_{j=1}^{5} \binom{5}{j} (-1)^{j-1} \sum_{m_1 \cdots m_j = m} \frac{1}{m_1 \cdots m_j} \log m_1 \mu(m_{j+1}) \cdots \mu(m_{2j}).
\]

With this, the sum \( \sum_{W < n \leq u} A(m) \chi(m) \) decomposes into a linear combination of \( O(L^{10}) \) terms, each of which is of the form
\[
\Sigma(u; M) = \sum_{m_1 \sim M_1} \cdots \sum_{m_{10} \sim M_{10}} a_1(m_1) \chi(m_1) \cdots a_{10}(m_{10}) \chi(m_{10}),
\]

where \( a_i(m) \) are given by (6.2), and \( M_j \) are positive integers satisfying (6.1) with \( M = W \). Here \( M \) denotes the vector \((M_1, M_2, \ldots, M_{10})\). We notice that for \( j = 1, 2, \ldots, 10 \), the function \( f_j(s, \chi) \) in (6.3) is a finite sum and has no poles for \( \sigma \geq 1/2 \). So by applying Perron’s summation formula and then shifting the contour to the left, the above \( \Sigma(u; M) \) becomes
\[
\frac{1}{2\pi i} \int_{1+1/L-iT_1}^{1+1/L+iT_1} F(s, \chi) \frac{u^s - W^s}{s} ds + O(L^2)
\]
\[
= \frac{1}{2\pi i} \left\{ \int_{1+1/L-iT_1}^{1/2-iT_1} + \int_{1/2+iT_1}^{1+1/L+iT_1} \right\} + O(L^2),
\]

where \( T_1 = 4k\pi(R + W) \). The integral on the two horizontal segments above is bounded by
\[
\max_{1/2 \leq \sigma \leq 1+1/L} |F(\sigma \pm iT_1, \chi)| \frac{u^\sigma}{T_1} \lesssim L,
\]
since \( W < u \ll 2W \) and
\[
|F(\sigma \pm iT_1, \chi)| \lesssim \prod_{j=1}^{10} |f_j(\sigma \pm iT_1, \chi)| \lesssim L \prod_{j=1}^{10} M_j^{1-\sigma} \lesssim W^{1-\sigma} L.
\]

Thus we get
\[
\Sigma(u; M) = \frac{1}{2\pi} \int_{-T_1}^{T_1} F(1/2 + it, \chi) \frac{u^{1/2+it} - W^{1/2+it}}{1/2 + it} dt + O(L^2).
\]
And therefore
\[ \int_{W}^{2W} e(\lambda u^k) \, d\Sigma(u, M) \]
\[ = \frac{1}{2\pi} \int_{-T}^{T} F(1/2 + it, \chi) \int_{W}^{2W} u^{-1/2 + it} e(\lambda u^k) \, du \, dt + (1 + |\lambda| W^k) L^2. \]

Here by making use of Lemmas 4.3 and 4.5 in [12], the inner integral is
\[ \ll W^{1/2} \min \left\{ \frac{1}{\min_{\nu < \epsilon < (2W)^k} |t + 2k\pi \lambda \nu|}, \frac{1}{\sqrt{1 + |t|}} \right\} \]
\[ \ll W^{1/2} \left\{ \begin{array}{ll}
\frac{1}{\sqrt{1 + |t|}} & \text{if } |t| \leq 4k\pi R, \\
\frac{1}{|t|} & \text{if } |t| > 4k\pi R,
\end{array} \right. \]
since \(|\lambda| W^k \leq R\). Therefore we have
\[ \sum_{\chi \mod q} \left| \Psi(\chi, \lambda, W) \right| \]
\[ \ll W^{1/2} \sum_{M} \sum_{\chi \mod q} \sum_{\lambda \neq \lambda_0} \int_{|t| \leq 4k\pi R} |F(1/2 + it, \chi)| \frac{dt}{\sqrt{1 + |t|}} \]
\[ + W^{1/2} \sum_{M} \sum_{\chi \mod q} \int_{4k\pi R < |t| < T} |F(1/2 + it, \chi)| \frac{dt}{|t|} + qRL^2. \]

By Lemma 6.1, we have
\[ \sum_{\chi \mod q} \int_{|t| \leq 4k\pi R} |F(1/2 + it, \chi)| \frac{dt}{\sqrt{1 + |t|}} \]
\[ \ll L \max_{1 \leq T \leq 2k\pi R} \frac{1}{\sqrt{1 + T}} \sum_{\chi \mod q} \int_{T < |t| < 2T} |F(1/2 + it, \chi)| \, dt \]
\[ \ll \max_{1 \leq T \leq 2k\pi R} \frac{1}{\sqrt{1 + T}} (qT + (qT)^{1/2} W^{3/10} + W^{1/2}) L^c \]
\[ \ll (qR^{1/2} + q^{1/2} W^{3/10} + W^{1/2}) L^c. \]

Similarly we have
\[ \sum_{\chi \mod q} \int_{4k\pi R < |t| \leq T_1} |F(1/2 + it, \chi)| \frac{dt}{|t|} \ll (q + q^{1/2} W^{3/10} R^{-1/2} + W^{1/2} R^{-1}) L^c. \]
These estimates together with (6.9) show that

$$\sum_{\chi \bmod q} \left| \sum_{m \sim W} A(m)\chi(m)e(\lambda m^c) \right| \leq \left\{ \left( R + (WR)^{1/2} \right) q + W^{1/5} q^{1/2} + W \right\} L^c.$$

This finishes the proof of Lemma 5.2. \(\square\)

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