AN ASYMPTOTIC FORMULA IN ADDITIVE NUMBER THEORY—II

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[Received February 13, 1976; revised November 30, 1976]

This paper is in some sense a sequel to our earlier paper I (Acta. Arith.; 28 (1976), 405–412) with the same title although the present paper is self contained.

Let \( \{b_j\} \) be an increasing sequence of integers with \( 3 \leq b_1 < b_2 < b_3 \ldots \) and \( \sum \frac{1}{b_j} < \infty \). Our principal object is to prove, under an assumption on the size of \( B(x) = \sum_{b_j \leq x} 1 \), that for any fixed position integer \( n \), the number of solutions of the equation \( n = p + t \) where \( t \) is a positive integer not divisible by any \( b_j \) and \( p \) is a prime exceeds \( \alpha \frac{n}{\log n} + o \left( \frac{n}{\log n} \right) \), where \( \alpha \) is a positive constant, and in particular \( \geq 1 \) for all sufficiently large \( n \). (The assumption on \( B(x) \) is \( B(x) = o \left( \frac{x}{\log x \log \log x} \right) \).

It will be clear from our proof that this can be weakened to \( B(x) = o \left( \frac{x}{\log x} \right) \) if a certain unproved hypothesis on the distribution of primes in arithmetic progressions is true. We prefer to state this hypothesis at the end of our proof.

Before starting the proof proper we make some reductions. Consider those \( b_j \) with \( \frac{b_j}{\varphi (b_j)} \geq 100 \). For these \( b_j \) we have \( \frac{\sigma (b_j)}{b_j} \geq 2 \) (\( \varphi \) is the Euler’s totient function and \( \sigma \) is the sum of the divisors) and so such \( b_j \) are abundant numbers (\( m \) is said to be abundant if \( \frac{\sigma (m)}{m} \geq 2 \)). It is easy to see that every multiple of an abundant number is also abundant. Defining an abundant number \( N \) to be primitive if \( N \) is the only abundant number which divides \( N \) we have the following:
Theorem (due to P. Erdős, On the density of abundant numbers, Jour. London Math. Soc. IX (1934), pp. 278-282, see theorem on page 281). The number of primitive abundant numbers not exceeding \( x \) is
\[
O \left( \frac{x}{(\log x)^2} \right).
\]

From \( \{b_j\} \) construct a new sequence by retaining as they are numbers \( b_j \) with \( \frac{b_j}{\varphi(b_j)} \leq 100 \) and replacing every other number by its maximum primitive abundant divisor. From the resulting set form a sequence in the increasing order by taking only the distinct ones. Suppose this sequence is \( \{b'_j\} \) where \( 3 \leq b'_1 < b'_2 < b'_3 \ldots \) (This sequence consists of un-replaced and replaced numbers of \( \{b_j\} \)). Note that \( \sum \frac{1}{\varphi(b'_j)} \) is convergent. Because \( \sum \frac{1}{\varphi(b'_j)} \) (this sum is over all \( b'_j \) satisfying \( X \leq b'_j \leq 2X \) and we adopt a similar notation elsewhere) = \( \sum_1 + \sum_2 \) where \( \sum_1 \) is part of the original \( \sum_{X, 2X} \frac{1}{\varphi(b_j)} \) without replacements and \( \sum_2 \) the rest. In \( \sum_1 \)
\[
\frac{b_j}{\varphi(b_j)} \leq 100 \quad \text{and so} \quad \sum_1 = O \left( \sum_{X, 2X} \frac{1}{b_j} \right) \quad \text{and} \quad \sum_2 = O \left( \sum'_{X, 2X} \frac{\log \log b'_j}{b'_j} \right)
\]
where \( \sum' \) denotes the restriction to the altered numbers and so \( \sum_2 \)
\[
= o \left( \frac{\log \log X}{(\log X)^2} \right) \quad \text{and this gives us the convergence of the required series.}
\]

Let \( \{d_i\} \) be the sequence \( 1 = d_1 < d_2 < d_3 \ldots \) of integers not divisible by any \( b_j \) and \( \{d'_i\} \) the sequence which corresponds to \( \{b'_j\} \) is a similar fashion. The sequence \( \{d_i\} \) includes \( \{d'_i\} \) and so the number of solutions of \( n = p + d_j \) is at least the number of solutions of \( n = p + d'_j \). We prove for the latter number a lower bound \( \gg \frac{n}{\log n} \) valid for all large enough \( n \). It follows that the number of solutions of \( n = p + d_j \) is also \( \gg \frac{n}{\log n} \) for all large enough \( n \). This is in fact the principal result we are looking for. (We however assume only at one place of
our proof that \( B(x) = o\left(\frac{x}{\log x \log \log x}\right) \) and at this point of our proof, even the weaker assumption \( B(x) = o\left(\frac{x}{\log x}\right) \) would suffice if we assume the truth of an unproved conjecture concerning the distribution of primes in arithmetic progressions). Note that \( \sum_{b_j' \leq x} 1 = \sum_{3} + \sum_{4} \) where \( \sum_{3} \) counts the unplaced \( b_j \) and \( \sum_{4} \) counts the replaced ones and so \( \sum_{3} = O(B(x)) \) and \( \sum_{4} = o\left(\frac{x}{(\log x)^2}\right) \). We may also note \( \sum_{x, 2x \neq b_j'} = \sum_{5} + \sum_{6} \) where \( \sum_{5} = O\left(\sum_{x, 2x : b_j} \frac{1}{b_j}\right) \) and \( \sum_{6} = o\left(\frac{\log \log X}{(\log X)^2}\right) \) are obvious portions of the sum. From now on we write \( a_i \) to mean \( b_i' \) and write \( A(x) = \sum_{a_i \leq x} 1 \). Throughout the paper we assume \( B(x) = o\left(\frac{x}{\log x}\right) \) which certainly gives \( A(x) = o\left(\frac{x}{\log x}\right) \). We now start the proof proper. We find it convenient to split it into several parts.

**Part I:** Estimation of \( \sum_{X_1 \leq a_i \leq x} \sum_{p=\#(\text{mod } a_i)} \sum_{1 \leq b \leq a_i} \) for a suitable \( X_1 \).

Denote the inner sum by \( \pi(n, a_i) \) and consider \( \sum_{a_i \leq n} \pi(n, a_i) \) for a given \( k = 0, 1, 2, \ldots \). We wish to estimate this uniformly in all parameters including \( k \). For any given \( k \) the sum is \( \sum_{a_i} O(2^k) (= O(A(n)) \) for bounded \( k \). Because trivially \( \pi(n, a_i) = O(2^k) \). Thus fixing up any arbitrarily large constant \( k_0 \), we have, \( \sum_{a_i \leq n} \sum_{n/2^{k+1} \leq a_i \leq n/2^k} \pi(n, a_i) = o\left(\frac{n}{\log n}\right) \).

We now introduce the points \( 2^{k/n} (k = 0, 1, 2, \ldots) \) and split up the range \( X_1 \leq a_i \leq n \) accordingly with proper modification at the end points. We have now to estimate \( S_i = \sum_{X_1 \leq a_i \leq n/2^k} \pi(n, a_i) \).

The contribution to this sum from those \( a_i \) (We now fix up till the end of the proof small positive constants \( \varepsilon, \delta, \delta_1 \), which are arbitrary but
independent of each other) satisfying,

\[(n, a_i) \leq \frac{n}{a_i (\log n/a_i) (\log \log n/a_i)^{1+\varepsilon}}\]

is

\[O \left( \sum_{k \geq k_0, n/2^{k} \leq n/2^{k+1}} \left( \frac{2^{k}}{k (\log k)^{1+\varepsilon}} \cdot \frac{n}{2^{k} \log (n/2^{k})} \right) \right) = O \left( \frac{n}{\log n} \right)\]

\[n \gg X \gg n^{1-\varepsilon}.\]

Consider the remaining portion \(S_2\) of the sum \(S_1\). We are led to estimate

\[\sum_{n/2^{k+1} \leq a_i \leq n/2^{k}} \pi (n, a_i)\]

where \(*\) denotes the restriction to those \(a_i\) which satisfy

\[\pi (n, a_i) \geq \frac{2^{k}}{k (\log k)^{1+\varepsilon}}.\]

First consider the contribution to \(S_2\) from those \(k\) for which the number of \(a_i\) does not exceed \(\frac{\delta_k n}{2^{k} k \log n}\). We observe that the contribution from such an integer \(k\) is by Brun-Titchmarsh Theorem

\[O \left( \sum_{a_i} \frac{n}{\varphi (a_i) \log (n/a_i)} \right)\]

where the sum over \(a_i\) is over an appropriate range depending on \(k\). We split this last sum into two parts according as \(a_i\) is unchanged or changed and we see that it is

\[O \left( \frac{n}{a_i \log (n/a_i)} \right) + o \left( \frac{n}{2^{k} (\log (n/2^{k}))^{1+\varepsilon}} \cdot \frac{2^{k} \log \log (n/2^{k})}{\log (2^{k})} \right)\]

\[= O \left( \frac{2^{k}}{k \log n} \cdot \frac{2^{k}}{\log (2^{k})} \right) + o \left( \frac{n \log \log (n/2^{k})}{k (\log (n/2^{k}))^{1+\varepsilon}} \right)\]

\[= O \left( \frac{\delta_k n}{k^{2} \log n} \right) + (\ldots)\]

It is easy to see that the last expressions when summed over from \(k = k_0\) to \([2^{8} \log n]\) is

\[O \left( \frac{\delta_k n}{\log n} \right) + o \left( \frac{n}{\log n} \right)\]

So far we imposed on \(X\) the only condition \(n \gg X \gg n^{1-\varepsilon}\). We now show that if \(X\) is properly chosen there do not exist any other values of \(k\) which make a further contribution to \(S_2\).

So we have now to consider only those \(k\) for which the number of
$a_i$s is $\geq \frac{\delta_i n}{2^k k \log n}$ and each $a_i$ satisfies $\pi(n, a_i) \geq \frac{2^k}{k (\log k)^{1+\varepsilon}}$. For such a fixed $k$ let $s$ be the number of $a_i$. Let us enumerate these $a_i$ (with a change of notation to avoid too many symbols) as
\[
\frac{n}{2^k k + 1} \leq a_1 < a_2 \leq \ldots < a_s \leq \frac{n}{2^k}
\]
where
\[
s \geq \frac{\delta_i n}{2^k k \log n} \quad \text{and} \quad Z_i = \pi(n, a_i) \geq \frac{2^k}{k (\log k)^{1+\varepsilon}}.
\]
Write
\[
n - p_j(0) = r_j(0) a_i \quad \text{where} \quad 1 \leq r_j(0) \leq 2^k.
\]
For any fixed $i$ the number of pairs $(p_j(0), p_{j'}(0)), (j_i \neq j')$ is $\geq \binom{Z_i}{2}$
\[
\frac{4^k}{4 k^3 (\log k)^{2+\varepsilon} \log n}
\]
and there are $s \geq \frac{\delta_i n}{2^k k \log n}$ values of $i$. Hence the total number of pairs is
\[
\geq \sum_i \binom{Z_i}{2} \geq \frac{\delta_i n 2^k}{4 k^3 (\log k)^{2+\varepsilon} \log n}.
\]
Let $t_1, t_2$ be integers satisfying $1 \leq t_1 \leq 2^k + 1$ and $1 \leq t_2 \leq 2^k + 1$.
It follows that if $N(t_1, t_2)$ denotes the total number of triplets $(t, j_i, j_a)$ with $r_j(0) = t_1, r_{j'}(0) = t_2$ then
\[
\sum_{(t_1, t_2) \neq (t, t_a)} \pi(t_1, t_2) \geq \frac{\delta_i n 2^k}{4 k^3 (\log k)^{2+\varepsilon} \log n}.
\]
The total number of pairs $(t_1, t_2)$ does not exceed $2^{2(k+1)}$ and hence there exists a pair $(t_1, t_2)$ (of course $t_1 \neq t_2$ and $1 \leq t_1 \leq 2^k + 1$, $1 \leq t_2 \leq 2^k + 1$) such that the simultaneous equations $n - p_1 = t_1 a$, $n - p_2 = t_2 a$ (where $a$ is a positive integer) have
\[
\geq \frac{\delta_i n}{2^k k^3 \log n (\log k)^{2+\varepsilon}} \quad (= Q \text{ say})
\]
solutions in triplets $(p_1, p_2, a)$. That is, there are $\geq Q$ values of $a$ ($1 \leq a \leq n/2^k$, $2^k \leq n^a$) for which $n - a t_1$ and $n - a t_2$ are both primes.
By the double sieve, the number of such integers $a$ is $O\left(\frac{n (\log \log n)^2}{2^k (\log n)^a}\right)$ (see page 45, Satz 4.2 of Prachar's book). This gives
\[
\frac{\delta_i \log n}{k^3 (\log k)^{2+\varepsilon}} = O\left(\frac{1}{\log n^a}\right).
\]
This gives a contradiction for large \( n \) if \( k \leq \left( \frac{\log n}{(\log \log n)^{1+3\varepsilon}} \right)^{1/3} \).

So we can choose \( X_1 \) to be
\[
X_1 = n \left\lfloor \frac{\log n}{(\log \log n)^{1+3\varepsilon}} \right\rfloor^{4+3\varepsilon}.
\]

This completes the proof that
\[
\sum_{x_i \leq a_i \leq n} \pi(n, a_i) = O\left( \frac{\delta_1 n}{\log n} \right) + o\left( \frac{n}{\log n} \right)
\]
where \( X_1 \) is chosen as stated just now (actually since the left side is independent of \( \delta_1 \) the first term on the right can be dropped).

**Part II. Estimation of**
\[
\sum_{i \geq L, a_i \leq n^{1-\delta}} \pi(n, a_i)
\]
where \( \delta > 0 \) is fixed and \( L \) is a large constant.

Applying Brun-Titchmarsh theorem the estimate for the required sum
\[
= O\left( \sum_{i \geq L} \frac{n}{\varphi(a_i) \log n} \right) = O\left( \frac{n}{\log n} \eta(L) \right)
\]
where \( \eta(L) \) tends to zero as \( L \) tends to infinity because of the convergence of \( \Sigma (\varphi(a_i))^{-1} \).

**Part III. Estimation of**
\[
\sum_{n^{1-\delta} \leq a_i \leq n \exp(-\log n)^{1+3\varepsilon} \log n^{-2}} \pi(n, a_i).
\]

We split up the range into minimum number intervals of the type \( X \leq a_i \leq 2X \) with modification at the end points and write it in the form \( \sum_x \sum_{X} \). Each \( \sum_x \) can be written \( \sum_{X}^{(1)} + \sum_{X}^{(2)} \) where \( (1) \) is over those \( a_i \) with
\[
\pi(n, a_i) \leq \frac{10^8 n}{\varphi(a_i) \log n}
\]
and \( (2) \) is over the remaining \( a_i \). By the convergence of \( \Sigma (\varphi(a_i))^{-1} \) we have easily
\[
\sum_x \sum_x^{(1)} = o\left( \frac{n}{\log n} \right).
\]
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\[ \sum_{x}^{(2)} \] is by Brun-Titchmarsh theorem

\[ O \left( \sum_{x}^{(3)} \frac{n}{\phi(a_{i}) \log \left( \frac{n}{a_{i}} \right)} \right) = o \left( \sum_{x}^{(2,1)} + \sum_{x}^{(2,2)} \right) \]

where \((2, 1)\) is over unchanged \(a_{i}\) and \((2, 2)\) is over the replaced ones.

Trivially

\[ \sum_{x}^{(2,2)} \sum_{x}^{(2,2)} = \sum_{x} O \left( \frac{n \log \log X}{(\log X)^{2} \log \left( \frac{n}{X} \right)} \right) = o \left( \frac{n}{\log n} \right). \]

Let \(A^{(1)}(X)\) be the number of unchanged \(a_{i}\) lying between \(X\) and \(2X\) for which

\[ \pi(n, a_{i}) \geq \frac{10^{8} n}{\phi(a_{i}) \log n}. \]

Then

\[ \sum_{x}^{(2,1)} \sum_{x}^{(2,1)} = O \left( \sum_{x} \frac{A^{(1)}(X)}{X} \frac{n}{\log \left( \frac{n}{X} \right)} \right). \]

By using a bound of the type \(A^{(1)}(X) = O(A(X))\) we can easily prove that the last quantity is \(o \left( \frac{n}{\log n} \right)\) if we assume \(A(X) = o \left( \frac{X}{\log X \log \log X} \right)\).

On the other hand we can also majorise \(A^{(1)}(X)\) by \(A^{(3)}(X)\) the number of all integers \(q\) satisfying \(X \leq q \leq 2X\) and \(\pi(n, q) \geq \frac{10^{8} n}{\phi(q) \log n}\) and make the

**Hypothesis.** Uniformly in \(n^{1-\delta} \leq X < 2X \leq \exp \left( - \frac{(\log n)^{1/3}}{(\log \log n)^{2}} \right)\) there holds \(A^{(2)}(X) = O(X (\log X)^{-5/3-\delta_{1}})\) for some constant \(\delta_{1} > 0\).

We see on replacing \(\log \frac{n}{X}\) by \((\log X)^{1/3} (\log \log X)^{-2}\), that

\[ \sum_{x}^{(2,1)} \sum_{x}^{(2,1)} = o \left( \frac{n}{\log n} \right). \]

**Part IV.** Lower bound for the number of solutions of \(n = p + d_{j}\).

Write \(A_{L}\) for the finite sequence \((a_{1}, a_{2}, \ldots, a_{L})\) and for any positive
integer $n$ write (In this section $t$ will stand for a positive integer)

$$f(n, A_L) = \sum_{n = p + t, t \equiv 0 \pmod{e_j}} 1.$$

We use a similar notation for any other finite or infinite sequence of positive integers in place of $A_L$. We choose $L$ to be a large but fixed integer and another fixed positive integer $h < L$ then certain odd primes $q_i (1 \leq i \leq h)$, in the following way. Since $a_j$ is never less than 3, it is divisible either by 4 or by an odd prime $q_j$ (in the latter case we fix $q_j$ to be the least odd prime which divides $a_j$). If in this process 4 occurs we designate it by $q_0$ and if it does not occur we just ignore the symbol $q_0$. Of course $q_j (j = 1$ to $h)$ need not be distinct. Let $A^*$ denote the finite sequence $(q_0, q_1, q_2, \ldots, q_h, a_{h+1}, a_{h+2}, \ldots, a_L)$. Before proceeding further it may be helpful to remark that $f(n, A_L) \geq f(n, A^*)$. For simplicity we write $A^{**}$ for the sequence obtained from $A^*$ by retaining only the distinct $q_j (1 \leq j \leq h)$. Next in $A^{**}$ retain only those $q_j (1 \leq j \leq h)$ which do not divide $n$ and afterwards only those $a_j (j > h)$ with $\prod_{1 \leq i \leq h} a_i = 1$. Call the resulting set

$$\tilde{A} = (q_0, q_1, \ldots, q_h, a'_{j+1}, a'_{j+2}, \ldots, a'_L)$$

where the notation is sufficiently self-explanatory. Let $S^*$ and $S^{**}$ be two finite sets of distinct integers and 1 be an element of $S^{**}$. We observe that the set

$$S^* \cap (S^{**} - 1)$$

has at least as many elements as $S^*$ plus the number of elements in $S^* \cap S^{**}$. Using this remark repeatedly one can verify that

$$f(n, A_L) \geq f(n, A^*) \geq f(n, q_0, q_1, q_2, \ldots, A, a'_{j+1}, a'_{j+2}, \ldots, a'_L) - J.$$

We now make the convention that $q_j (1 \leq j \leq J)$ are in the increasing order. We next replace all $a'_j (j > J)$ which are even but not multiples of 4 by $\frac{1}{2}a'_j$ and designate the set resulting from $a'_j (J < j \leq T)$ in the increasing order by $a''_j (J < j \leq T)$. Our last lower bound for $f(n, A_L)$ is
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\[ \geq f(n, 4, q_1, q_2, \ldots, q_J, a_{j+1}^*, a_{j+2}^*, \ldots, a_J^*) - J \]

\[ \geq f(n, 4, q_1, q_2, \ldots, q_J) - J \]

\[ - \sum_{v = J + 1}^{\tau} \sum_{n = p + 1}^{\tau} \sum_{t \equiv a \mod q_j \text{ for all } j \in (o < j < J), t = a (\mod a_j^*)} 1. \]

Here (and from now on) we put \( q_o = 4 \). Note that the present \( q_o \)
always denotes 4 whether the old \( q_o \) already introduced may or may
not exist. This will not cause any confusion since the purpose of
introducing the old \( q_o \) is over and we do not need it any more. By
using the prime number theorem for arithmetic progressions and a simple
argument of Eratosthanes it is not hard to verify the following steps
(the notations are obvious and we do not explain them)

\[ f(n, q_o, q_1, \ldots, q_J) = \pi(n) - \sum_{i} \pi(n, q_i, n) + \sum_{i \neq j} \pi(n, [q_i q_j], n) - + \ldots \]

\[ = \frac{n}{\log n} \prod_{0 < i < J} \left( 1 - \frac{1}{\varphi(q_i)} \right) + O_h \left( \frac{n}{(\log n)^2} \right) \]

In the sum over \( v \) the \( v \)-th term is

\[ = \pi(n, a_v^*, n) - \sum_{i} \pi(n, [a_v^*, q_i], n) \]

\[ + \sum_{i \neq j} \pi(n, [a_v^*, q_i q_j], n) - + \ldots \]

\[ = \frac{n}{\varphi(a_v^*)} \log n \prod_{0 < i < J} \left( 1 - \frac{1}{\varphi(q_i)} \right) + O_h, \quad a_v^* \left( \frac{n}{(\log n)^2} \right) \]

Thus \( f(n, A_L) \) exceeds

\[ \frac{n}{\log n} \prod_{0 < i < J} \left( 1 - \frac{1}{\varphi(q_i)} \right) \left( 1 + O \left( \sum_{v \geq J + 1} \frac{1}{\varphi(a_v^*)} \right) \right) + O_L \left( \frac{n}{(\log n)^2} \right) \]

From our definition of \( a_v^* \) and the convergence of \( \sum \frac{1}{\varphi(a_v)} \) it follows
that the last expression exceeds

\[ \frac{Cn}{\log n} + O_L \left( \frac{n}{(\log n)^2} \right) \]

where \( C (> 0) \) is independent of \( L \) and \( n \) but depends only on \( h \). Now
if we fix first a large \( h \) and then a larger \( L \), we have
\[ f(n, A) \geq f(n, AL) - \sum_{\nu \geq L + 1} \sum_{n = \nu p + t} 1 \]
\[ \geq \frac{C_1 n}{\log n} (C_1 > 0 \text{ independent of } n) \]

provided \( n \geq n_0 \), by the results of parts I, II and III.

**Part V. Statement of the main theorem.** Collecting together we state

**Theorem.** Let \( \{b_j\} j = 1, 2, \ldots \) be a finite or an infinite sequence of integers satisfying \( 3 \leq b_1 < b_2 < b_3 \ldots \) and \( \sum \frac{1}{b_j} < \infty \). Let \( 1 = d_1 < d_2 < d_3 \ldots \) be the sequence of all integers \( d_i \) \((i = 1, 2, 3, \ldots)\) which are not divisible by any \( b_j \). Let \( B(x) = \sum_{b_j \leq x} 1 \) and \( B(x) = o \left( \frac{x}{\log x \log \log x} \right) \).

Then the number solutions for any fixed \( n \geq n_0 \) (a large constant depending on the constants implied by the sequence and the nature of \( o(\ldots) \) of the equation

\[ n = p + d_j \ (p \text{ prime}) \]

is \( \geq \frac{n}{\log n} \) and in particular \( \geq 1 \).

**Remark.** The conclusion of the theorem is valid even with the milder assumption \( B(x) = o \left( \frac{x}{\log x} \right) \) if the following hypothesis regarding the distribution of primes in arithmetic progressions is true.

**Hypothesis.** Let \( \delta > 0 \) be any small constant and

\[ n^{1-\delta} \leq X < 2X \leq n \exp \left( -(\log n)^{1/3} (\log \log n)^{-2} \right) \]

Then the number of integers \( q \) satisfying \( X \leq q < 2X \) and

\[ \pi(n, q, n) \geq \frac{10^\delta n}{\varphi(q) \log n} \text{ is } O_\delta \left( \frac{X}{(\log X)^\lambda} \right) \]

where \( \lambda > \frac{\delta}{2} \) is a constant.

The following hypothesis is also sufficient and is perhaps simpler to prove than the one stated above.
HYPOTHESIS. Let $n^{1-\delta} \leq X < 2X \leq n \operatorname{Exp}(-(\log n)^{1/3})$. Then the number of integers $q$ satisfying $X \leq q \leq 2X$ for which

$$\pi(n, q, n) \geq n (\log \log n)^{\delta} (q \log n)^{-1}$$

is $o(X \log X \log \log X)^{-1}$.

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