THE HITTING DISTRIBUTIONS OF A LINE FOR TWO DIMENSIONAL RANDOM WALKS

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ABSTRACT. For every irreducible random walk on \( \mathbb{Z}^2 \) with zero mean and finite \( 2 + \delta \) absolute moment (\( 0 \leq \delta < 1 \)) we obtain fine asymptotic estimates of the probability that the first visit of the walk to the horizontal axis takes place at a specified site of it.

1. INTRODUCTION AND RESULTS

In this paper we consider an irreducible random walk on the square lattice \( \mathbb{Z}^2 \) having zero mean and finite \( 2 + \delta \) absolute moment (\( 0 \leq \delta < 1 \)) and obtain fine asymptotic estimates of the hitting distribution of the horizontal axis \( \{ (s,0) : s \in \mathbb{Z} \} \), when the walk is started from a point \((0,n)\) on the vertical axis, as \(|s| + |n| \to \infty\). This distribution, denoted by \( H_n(s) \), would play a significant role in the theory of two dimensional random walks, but does not seem to have received the sufficient investigation it would deserve since the advent of Donsker’s invariance principle. According to that principle the distribution \( H_n(s) \), if suitably normalized, is asymptotically equivalent as \( n \to \infty \) to the Cauchy distribution \( |n|/\pi(n^2 + s^2) \). This equivalence however is in the topology of weak convergence of probability measures and does not imply the equivalence in any stronger sense such as point-wise comparability even when \( n \) tends to infinity with \( |s/n| \) bounded away from infinity, let alone when \( n \) remains in a finite interval or gets indefinitely large but in a small order of \( s \). In our asymptotic formula the leading term of \( H_n(s) \) is determined in all cases of \(|s| + |n| \) tending to infinity, entailing a fairly uniform equivalence in a point-wise level so that even the tail of the probability (i.e., its asymptotic behavior for large \( s \)) is in a good agreement with that of the Cauchy distribution (but with the factor \(|n|\) replaced by the potential of the one dimensional walk of the vertical component). The proofs are done by the Fourier analytic method.

Let \( p(x) = p(x_1, x_2) \), \( x = (x_1, x_2) \in \mathbb{Z}^2 \) be a probability distribution on \( \mathbb{Z}^2 \) which is aperiodic in the sense that the set \( \{ x \in \mathbb{Z}^2 : p(x) > 0 \} \) is not included in any proper subgroup of \( \mathbb{Z}^2 \), and satisfies

\[
\sum x p(x) = 0 \quad \text{and} \quad \sum |x|^{2+\delta} p(x) < \infty,
\]

where \( 0 \leq \delta < 1 \), and consider the random walk \( S_n = (S_n^{(1)}, S_n^{(2)}) \) on \( \mathbb{Z}^2 \) with i.i.d. increments whose one-step transition probability is given by \( p(x,y) = p(y-x) \).

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Denote by $P_x$ the probability law of the walk starting at $x \in \mathbb{Z}^2$ and by $E_x$ the expectation by $P_x$. Let $L = \{ x \in \mathbb{Z}^2 : x_2 = 0 \}$ (the first coordinate axis). Then $H_n(\cdot)$, the hitting distribution mentioned above, is written as

$$H_n(s) = P_{(0, 0)}[S_n^{(1)} = s, \tau(L) = s],$$

where $\tau(L) = \inf\{ n > 0 : S_n \in L \}$, the first positive time when $S_n$ visits $L$.

Let $Q$ be the covariance matrix of $S_1$ under $P_0$ and write $Q(\theta)$, $\theta = (\theta_1, \theta_2) \in \mathbb{R}^2$ for the quadratic form associated to it so that $Q(\theta) = \theta \cdot Q \theta$ and

$$Q(\theta) = E_0[(S_1 \cdot \theta)^2] = \sigma_1^2 \theta_1^2 + 2\sigma_1 \theta_1 \theta_2 + \sigma_2^2 \theta_2^2,$$

where $\sigma_{12} = E_0[S_{11} S_{12}]$ and $\sigma_j = \sqrt{E[|S_{1j}|^2]}$ ($j = 1, 2$). Let $\sigma = |\det Q|^{1/4}$ and define the norm

$$\|x\| = \sigma \cdot |Q^{-1}(x)| = \sigma^{-1} \sqrt{\sigma_2^2 x_1^2 - 2\sigma_1 \theta_1 x_1 x_2 + \sigma_1^2 x_2^2},$$

where $Q^{-1}(x)$ stands for the quadratic form for the inverse matrix $Q^{-1}$ of $Q$. Let $a(n)$ ($n \in \mathbb{Z}^2$) be the potential function of the one dimensional random walk $S_{n}^{(2)}$:

$$a(n) = \sum_{k=0}^{\infty} (P_0[S_{k}^{(2)} = 0] - P_0[S_{k}^{(2)} = -n]),$$

where the series converges and its sum is larger than or equal to $|n|/\sigma_2^2$ (cf. Spitzer [7, P28.8, P31.1]). Put $a^*(n) = a(n)$, $n \in \mathbb{Z} \setminus \{0\}$ and $a^*(0) = 1$. For $s, n \in \mathbb{Z}$ define $\tilde{s}$ by

$$\tilde{s} = \tilde{s}(s, -n) = s + \mu n, \quad \text{where} \quad \mu = \sigma_{12}/\sigma_2^2.$$

Put $\lambda = \sigma^2/\sigma_2^2$, so that

$$\|(s, -n)\|^2 = \lambda^{-1} \tilde{s}^2 + \lambda n^2.$$

It is recalled that $0 \leq \delta < 1$ in the moment condition (1.1).

**Theorem 1.1.** For each $\varepsilon > 0$,

$$H_n(s) = \frac{1}{\pi} \frac{|n|}{\|(s, -n)\|^2} \left[ 1 + o\left( \frac{1}{|n|^\delta} \right) \right] \quad (|n| > \varepsilon|s|, |n| \to \infty),$$

$$H_n(s) = \frac{1}{\pi} \frac{\sigma_2^2 a^*(n)}{\tilde{s}^2/\lambda} \frac{\lambda^2 |n|^3}{\|(s, -n)\|^2 \tilde{s}^2} \left[ 1 + o\left( \frac{\log |s|}{|s|^\delta} \right) \right] \quad (|\tilde{s}| > \varepsilon|n|, |\tilde{s}| \to \infty).$$

Here $o(1/|n|^\delta)$ in (1.2) is uniform for $|s| < |n|/\varepsilon$; similarly $o(|s|^{-\delta} \log |s|)$ in (1.3) is uniform for $|n| < |s|/\varepsilon$.

**Remark 1.** (i) In the overlapping region $\varepsilon|n| < |s| < \varepsilon^{-1}|n|$ the two formulae (1.2) and (1.3) coincide except for the logarithmic factor in the error term owing to the asymptotic relation $a(n) = \sigma_2^{-2} |n|(1 + o(|n|^{-\delta}))$ as $|n| \to \infty$ (cf. [14]: Corollary 6.1) and the identity

$$\frac{\lambda^2 |n|^3}{\|(s, -n)\|^2 \tilde{s}^2} = \frac{|n|}{\tilde{s}^2/\lambda} - \frac{|n|}{\|(s, -n)\|^2}.$$

(ii) If (1.1) is true for $1 \leq \delta < 2$, the formula (1.2) (resp. (1.3)) remains valid if we add to its right side an extra term that is $O(1/n^2)$ (resp. $O(n/s^3)$); in the case
when all the third moments of \( S_1 \) under \( P_0 \) vanish, the extra term is simplified and takes on the form

\[
\frac{C^*}{\pi} \cdot \frac{\lambda n - \lambda^{-1} \hat{s}^2}{\| (s, -n) \|^2} \quad \text{(resp.} \quad \frac{C^*}{\pi} \left( \frac{\lambda n - \lambda^{-1} \hat{s}^2}{\| (s, -n) \|^4} + \frac{\lambda}{\hat{s}^2} \right) \text{)}
\]

where \( C^* = (2\pi)^{-1} \int_{-\pi}^\pi \sigma_2^2 1 - \psi(0, t)^{-1} - (1 - \cos t)^{-1} \right] dt \). The constant \( C^* \) is non-negative and vanishes if and only if the walk is continuous in the vertical direction (namely \( p((x_1, x_2)) = 0 \) if \( |x_2| \geq 2 \) \( \left[ 14 \right] \)).

(iii) In the case \( \delta = 0 \) the formula \( \left[ 1.3 \right] \) of Theorem \( \left[ 1.1 \right] \) does not determine the precise leading term since the error term in the square brackets may be unbounded. To get the error of order \( o(1) \) one needs to impose some additional conditions (see Theorem \( \left[ 1.3 \right] \) and Remark 2 below).

(iv) If the walk is symmetric relative to \( L \) and continuous in the vertical direction, then the reflection principle (cf. \([7], p.155\)) can be applied to derive the estimates \( \left[ 1.3 \right] \) and Remark 2 below.

(v) That \( a^*(n) \) appears in the leading term on the right side of \( \left[ 1.3 \right] \) may be explained by means of the formula \( P_{(0, n)}|S_k^{(2)}| \geq K \) for some \( k < \tau(L) \) \( = \sigma_2^2 a^*(n)/K + o(n/K) \) as \( K \to \infty \) uniformly for \( |n| < K \) (cf. \([14]\)) for the hitting site \( S_{\tau(L)} \) to be far from the origin the walk is most likely to pass once across a large ordinate level before arriving at \( L \).

Write \( X \) and \( Y \) for \( S_1^{(1)} \) and \( S_1^{(2)} \), the first and second components of \( S_1 \), respectively, and \( P \) and \( E \) for \( P_0 \) and \( E_0 \), respectively, so that \( \sigma_{12} = EXY \), etc. Define \( X \) by

\[
\tilde{X} = X - \mu Y.
\]

A natural sufficient condition for \( H_0(s) \) to behave like const \( \times \hat{s}^{-2} \) as \( \hat{s} \to \infty \) turns out to be

\[
E[\tilde{X}^2 \log |\tilde{X}|] < \infty,
\]

where \( t \log t = 0 \) for \( t = 0 \). We also write \( a \lor b = \max\{a, b\} \) and \( a \land b = \min\{a, b\} \) for \( a, b \) real.

**Theorem 1.1.** Suppose that \( \left[ 1.6 \right] \) holds. Then, as \( |s| \lor |n| \to \infty \),

\[
H_n(s) = \frac{1}{\pi} \frac{\sigma_2^2 a^*(n)}{\| (s, -n) \|^2} [1 + o(1)].
\]

(Here \( o(1) \to 0 \) whenever \( |s| \lor |n| \to \infty \).)

The next theorem is of interest in the case when \( \left[ 1.6 \right] \) is violated.

**Theorem 1.2.** Let \( \varepsilon > 0 \). Then, for \( |n| < |s| \),

\[
H_n(s) = \frac{\lambda}{\pi} \left( \frac{\sigma_2^2 a^*(n)}{\hat{s}^2/\lambda} - \frac{\lambda^2|n|^3}{\| (s, -n) \|^4 \hat{s}^2} \right) (1 + o(1)) + \frac{a^*(n)}{\pi \lambda \hat{s}^2} M_\varepsilon(s)(1 + o_0(1)),
\]

where

\[
M_\varepsilon(s) = \mathbb{E} \left[ \tilde{X}^2 \log \frac{|\tilde{s}|}{|X - \tilde{s}| \lor |Y| \lor 1} : |\tilde{X} - \tilde{s}| \lor |Y| < \varepsilon |\tilde{s}| \right],
\]

and \( o(1) \to 0 \) uniformly in \( n \) and \( o_0(1) \to 0 \) boundedly as \( |s| \to \infty \). Moreover \( 1 + o_0(1) = m(s, n) + o(1) \) with \( 0 \leq m(s, n) \leq 1 \) and \( o(1) \) as above.
In the case when $X$ and $Y$ are stochastically independent of each other, the leading term in (1.7) can be derived by using the formula $P_{(a,n)}[\tau(L) > k] = a^*(n)\sigma_2/\sqrt{\pi k}/2(1 + o(1)) \\ (k \to \infty)$ (cf. §32 of [7]; see [12] for uniformity in $n$) as well as the local limit theorem applied to $S_n^{(2)}$; this also provides another explanation for the factor $a^*(n)$ to appear in the leading term. Even if $X$ and $Y$ are independent, one still needs to suppose the condition (1.6) to ensure (1.7).

Remark 2. (i) Consider the case $\delta = 0$. If $|n| > |s|$, the formula (1.2) provides the correct leading term, while if $|\tilde{s}|/(|n| \vee 1) \to \infty$ we have only

$$H_n(s) = \frac{1}{\pi} \frac{\sigma^2}{\tilde{s}^2/\lambda} \left[ 1 + o(\log |\tilde{s}|) \right] \quad (|\tilde{s}| > |n|),$$

which cannot be improved: in fact by using Theorem 1.3 one can readily infer that for any increasing function $h(t) > 0$ such that $h(t)/\log t \to 0$ as $t \to \infty$ there exists a probability $p$ such that $p$ satisfies (1.1) (with $\delta = 0$) and the error term in the square brackets above is not bounded by $h(|\tilde{s}|)$.

(ii) In a similar sense the condition (1.6) cannot be relaxed for validity of (1.3): for any $h(t) > 0$ such as in (i) there exists a probability $p$ satisfying (1.1) such that $E[X^2h(X)] < \infty$ and for each $n$, $\limsup_{s \to \infty} H_n(s)s^2 = \infty$. On the other hand the formula (1.7) of Theorem 1.2 may hold for $p$ which fails to satisfy (1.0) if the marginal $P[X = s]$ has sufficiently nice asymptotic behavior as $s \to \infty$: e.g., as Theorem 1.3 shows, if $P[X = s] \leq C|s|^2$, then (1.7) is true regardless of condition (1.0). Theorem 1.3 also implies that one-sided moment conditions $E[X^2 \log |X|; \pm X > 1] < \infty$ entail the corresponding one-sided asymptotic forms $\sigma^2/\pi a^*(n)/s^2$ of $H_n(s)$ (as $s \to \infty$).

For higher dimensional walks we have analogous results to Theorem 1.2 as discussed in Section 10.

The situation is rather simpler: the formula corresponding to (1.7) holds true under $\delta = 0$ and its proof is substantially simplified. From the estimate of $H_n(s)$ as given in Theorem 1.1 one can derive (cf. [11]) that of the hitting distribution of the negative half of $L$ by considering the one dimensional random walk that is a trace of $S_n$ left on $L$ and applying the theory of ladder processes as found in [7] or in [1]. Such a result in turn would give some precise estimate of the hitting distributions of long segments on $L$, of which certain upper bounds are obtained by Kesten [3] for simple random walk and by Lawler and Limic [3] for random walks with finite $5/2 + \delta$ absolute moment. In a separate paper we compute the asymptotic form of the Green function of the domain $Z^2 \setminus L$, which is to entail a (less precise) version of Theorem 1.1 but the computation is more involved than these given in this paper and indeed relies on some results in this paper.

We conclude this section with the following result on the integrated tail $E_n(s) = H_n(s) + H_n(s + 1) + \cdots$, which is much easier to obtain. The result is stated only for $\delta = 0$.

**Theorem 1.4.** As $\tilde{s}/(|n| \vee 1) \to \infty$, $E_n(s) \to \frac{\sigma^2 a^*(n)}{\pi \tilde{s}/\lambda} (1 + o(1))$.

It is noted that in the case when $\tilde{s}/n$ remains bounded, the invariance principle gives the correct limit value: for each $K > 0$, $E_n(s) = \frac{1}{2} - \frac{1}{\pi} \arctan(\tilde{s}/\lambda n) + o(1)$ as $n \to \infty$ with $|\tilde{s}|/n < K$. 
2. Preliminary formulae and estimates

Let \( \hat{H}_n(t) \) \((t \in \mathbb{R})\) denote the characteristic function of the probability distribution \( H_n(\cdot) \):

\[
\hat{H}_n(t) = \sum_{s \in \mathbb{Z}} H_n(s)e^{ist}.
\]

Define
\[
\psi(\theta) = \psi(\theta_1, \theta_2) = E_0\left[e^{i\theta . S_1}\right] \quad (\theta = (\theta_1, \theta_2) \in [-\pi, \pi]^2)
\]
and
\[
(2.1) \quad \pi_k(t) = \frac{1}{2\pi} \int_{-\pi}^{\pi} e^{-ikt} \frac{dl}{1 - \psi(t, l)} \quad (t \neq 0).
\]

Lemma 2.1. If \(0 < |t| \leq \pi\), then
\[
(2.2) \quad \hat{H}_n(t) = \frac{\pi - n(t)}{\pi_0(t)} \quad (n \neq 0)
\]
and
\[
(2.3) \quad \hat{H}_0(t) = 1 - \frac{1}{\pi_0(t)}.
\]

The proof of this lemma is standard and postponed until the last section (Appendix (A)).

We must compute
\[
(2.4) \quad H_n(s) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{\pi - n(t)}{\pi_0(t)} e^{-ist} dt \quad (n \neq 0).
\]

In carrying out the computation we suppose that \(Q\) is diagonal:

\[
Q(t, l) = \sigma_1^2 t^2 + \sigma_2^2 l^2,
\]
which gives rise to no loss of generality as will be discussed in Section 10 (see (10.2)).

From (1.1) one obtains
\[
1 - \psi(t, l) = \frac{1}{2} Q(t, l) (1 + o(|t|^\delta + |l|^\delta)) \quad (|t| \vee |l| \to 0)
\]
and then, changing the variable of integration by \(u = l/t\), one finds that as \(t \to 0\),
\[
(2.5) \quad |t|\pi_0(t) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{|t|dl}{1 - \psi(t, l)} = \frac{1}{\pi} \int_{-\pi/|t|}^{\pi/|t|} \frac{dl}{Q(1, l)} + o(|t|^\delta)
\]
(see Lemma 2.3 below for evaluation of the error term) and the integral on the right side equals \(\pi/\sigma^2 + O(t)\), so that
\[
(2.6) \quad 1/\pi_0(t) = \sigma^2|t| + o(|t|^{1+\delta}).
\]

Our main task for proof of the first formula (1.2) of Theorem 1.1 is to derive from

\[
(2.7) \quad H_n(s) = \frac{1}{(2\pi)^2} \int_{-\pi}^{\pi} \frac{e^{-ist}}{\pi_0(t)} \int_{-\pi}^{\pi} \frac{e^{isl} dl}{1 - \psi(t, l)}
\]
the following lemma, whose proof will be given in the next section.

Lemma 2.2. For each \(\varepsilon > 0\), uniformly for \(|s| < |n|/\varepsilon\) as \(|n| \to \infty\),
\[
(2.8) \quad H_n(s) = \frac{\sigma^2}{(2\pi)^2} \int_{-\pi}^{\pi} |t| \cos st dt \int_{-\infty}^{\infty} \frac{2 \cos nl dl}{Q(t, l)} + o\left(\frac{|n|^{1-\delta}}{s^2 + n^2}\right).
\]
Using the following identities for the well-known pair of cosine transforms
\[
\frac{\sigma^2 |t|}{2\pi} \int_{-\infty}^{\infty} 2 \cos nl \, dl = e^{-\lambda |nt|} \quad \text{and} \quad \int_{-\infty}^{\infty} e^{-\lambda |nt|} \cos s \, dt = \frac{2\lambda |n|}{s^2 + \lambda^2 n^2}
\]
\((\lambda = \sigma_1/\sigma_2)\) as well as the trivial estimate \(\int_{|t|>\pi} e^{-\lambda |nt|} \cos s \, dt = O(e^{-\lambda |n|})\), we immediately deduce from Lemma 2.2 the formula (1.2), which may be written as
\[
H_n(s) = \frac{1}{\pi} \cdot \frac{\lambda |n|}{s^2 + \lambda^2 n^2} \left[ 1 + o\left( \frac{1}{|n|^4} \right) \right] \quad (|\hat{s}| < |n|/\varepsilon).
\]

In the case \(|s| > |n|\) the leading term is to be different from one that comes up above, and it will be desirable to arrange the expression on the right side of (2.4) so that an integral that is to become the minor term is separated from one involving the main term. This is achieved by rewriting \(H_n\) as
\[
\hat{H}_n(t) = \frac{\pi - n(t) - \pi_0(t) + a(n)}{\pi_0(t)} + 1 - \frac{a(n)}{\pi_0(t)} \quad (n \neq 0).
\]
Under the condition \(E_0(|Y|^2) < \infty\) (remember \((X,Y)\) is written for \((S^{(1)}, S^{(2)})\)), we have
\[
a(n) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{1 - e^{inl}}{1 - \phi(l)} \, dl, \quad \text{where} \quad \phi(l) = \psi(0, l).
\]
(Cf. [3]; also see [7] (7.28) but under the symmetry assumption on the law of \(Y\).) Set
\[
e_n(t) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \left[ \frac{1}{1 - \psi(t, l)} - \frac{1}{1 - \phi(l)} \right] (e^{inl} - 1) \, dl
\]
and
\[
\rho(t) = \frac{1}{\pi_0(t)}
\]
so that \(e_n(t) = \pi_n(t) - \pi_0(t) + a(n)\) and
\[
\hat{H}_n(t) = \rho(t) e_n(t) + 1 - a^*(n) \rho(t)
\]
(valid also for \(n = 0\)). We shall show
\[
\frac{1}{2\pi} \int_{-\pi}^{\pi} \rho(t) e_n(t) e^{-ist} \, dt = \frac{\sigma^2}{\pi |s|^2} + o\left( \frac{\log |s|}{|s|^{2+\sigma}} \right)
\]
and
\[
\frac{1}{2\pi} \int_{-\pi}^{\pi} \rho(t) e_n(t) e^{-ist} \, dt = \frac{\lambda^2 |n|^2}{\pi \|(s, -n)\|^2 s^2} + o\left( \frac{n \log |s|}{|s|^{2+\sigma}} \right).
\]
The second formula (1.3) of Theorem 1.1 immediately follows from these.

The error terms in (2.8), (2.12) and (2.13) are evaluated by integration by parts. In the case \(|s| < |n|\) we shall integrate by parts with respect to \(t\) to derive the error estimate in (2.8) which is at most \(o(1/n)\), whereas in the case \(|s| > |n|\) we seek an error estimate of \(o(n/s^2)\) or better and thereby need to perform integration by parts twice with respect to \(t\). At the final steps of these processes we shall apply Lemma 11.2 in the former case and Lemma 11.4 in the latter, both of which are derived by standard methods in Fourier analysis. The proofs of Theorems 1.2 and 1.3 involve certain methods that are less standard.
A change of variables as being made in the derivation of (2.5) will be of repeated use in the succeeding sections (sometimes with the roles of \( t \) and \( l \) reversed), and we here present trite estimates of integrals as involved in (2.5) as the following lemma for convenience of later citation.

**Lemma 2.3.** Let \( \delta, \alpha \) and \( m \) be real numbers such that \( \delta \geq 0 \) and \( \alpha > -1 \). If \( b(t, l) \) is a continuous function on \([-1, 1] \times [-1, 1]\) such that \( b(t, l) = o(|t|^{\delta} + |l|^{\delta}) \) as \( |t| \vee |l| \to 0 \), then as \( t \to 0 \),

\[
\int_{-1}^{1} \frac{|l|^\delta b(t, l)}{|Q(t, l)|^m} dl = \begin{cases} o(|t|^{\alpha+\delta+1-2m}) & \text{if } \alpha + \delta + 1 - 2m < 0, \\ o(|t|^{\alpha}) & \text{if } \alpha + \delta + 1 - 2m = 0. \end{cases}
\]

The rest of the paper is organized as follows. The proof of Theorem 1.1 is finished in Section 3 except for two lemmas which are proved in Section 4. In Section 5 we give some detailed estimates of \( e_n \), which are needed for the proof of Theorems 1.2 and 1.3 given in Sections 6 and 7, respectively. Theorem 1.4 is proved in Section 8. Section 9 is devoted to the case when \( \delta \geq 1 \) in our basic moment condition (1.1). In Section 10 we indicate a way to reduce the problem to the case when \( Q \) is diagonal; we also briefly discuss the higher dimensional case as mentioned before. Section 11, the last section, is an Appendix consisting of (A) the proof of Lemma 2.2 and (B) several lemmas of a Fourier analytical nature.

### 3. Proof of Theorem 1.1

In Sections 3 through 8 we suppose that \( Q \) is diagonal: \( Q(t, l) = \sigma_2^2 t^2 + \sigma_1^2 l^2 \). The proof of Theorem 1.1 given below is a continuation of its outline advanced in the preceding section.

The case \( |s| < |n| \). We have only to prove Lemma 2.2, namely to evaluate the difference of the leading term on the right side of (2.8) from \( H_n(s) \). Write it as \((2\pi)^{-2}(r + \bar{r})\) so that

\[
(2\pi)^2 H_n(s) = \sigma^2 \int_{-\pi}^{\pi} |t| e^{-ist} dt \int_{0}^{\infty} \frac{4 \cos nl}{Q(t, l)} dl + r(s, n) + \bar{r}(s, n),
\]

where

\[
r(s, n) = \int_{-\pi}^{\pi} \rho(t) e^{-ist} dt \int_{-\pi}^{\pi} \left[ \frac{1}{1 - \psi(t, l)} - \frac{2}{Q(t, l)} \right] e^{inl} dl
\]

and

\[
\bar{r}(s, n) = \int_{-\pi}^{\pi} (\rho(t) - \sigma^2 |t|) e^{-ist} dt \int_{0}^{\infty} \frac{Q(t, l)}{4 \cos nl} dl - \int_{-\pi}^{\pi} \sigma^2 |t| e^{-ist} dt \int_{0}^{\infty} \frac{Q(t, l)}{4 \cos nl} dl
\]

(recall \( \rho(t) = 1/\pi_0(t) \)). We carry out the estimation of \( r \) only: that of \( \bar{r} \) is similar but only simpler because of the absence of a \( \sin nl \) part in it (see (3.2) below). On first reversing the order of integration and then integrating by parts (with respect to \( l \)),

\[
r(s, n) = \frac{1}{in} \int_{-\pi}^{\pi} e^{inl} dl \int_{-\pi}^{\pi} F(t, l) e^{-ist} dt,
\]

where

\[
F(t, l) = \frac{-\partial \psi(t, l) \rho(t)}{(1 - \psi(t, l))^2} - \frac{4\sigma_2^2 \rho(t)}{|Q(t, l)|^2}
\]
(\(\partial_t \) indicates partial differentiation). From the readily verified bounds
\[
|F(t, l)| = o\left(\frac{|t|(|t|^{\delta} + |l|^{\delta})}{(t^2 + l^2)^2}\right) \quad \text{and} \quad |\partial_tF(t, l)| = o\left(\frac{|t|(|t|^{\delta} + |l|^{\delta})}{(t^2 + l^2)^2}\right) \quad (|t| \vee |l| \to 0),
\]
one employs Lemma 2.3 to deduce that
\[
\int_{-\pi}^{\pi} |F(t, l)|\,dt = o(|t|^{\delta-1}) \quad \text{and} \quad \int_{-\pi}^{\pi} |\partial_tF(t, l)|\,dt = o(|t|^{\delta-2}).
\]
If \(\delta > 0\), these two estimates imply the required one, i.e., \(\sup_s |r(s, n)| = o(|n|^{-1-\delta})\), according to the last assertion of Lemma [11.2] in the Appendix (with the roles of \(n\) and \(s\) reversed: the convergence in Lemma [11.2] is as \(s \to \infty\) and uniform in \(n\) in reverse to the present situation).

In the case \(\delta = 0\) the same reasoning is inadequate and we need to look at the inner integral in (3.1) more closely. To this end we decompose \(r = r_e + r_o\), where
\[
(3.2) \quad \left\{\begin{array}{l}
r_e \equiv \int_{-\pi}^{\pi} \rho(t) e^{-ist} \,dt \\
r_o \equiv \int_{-\pi}^{\pi} \left[ \frac{1}{1 - \psi(t, l)} - \frac{2}{Q(t, l)} \right] \{\cos n\ell \} \,d\ell.
\end{array}\right.
\]

Lemma 3.1. \(\sup_s |r_o(s, n)| \vee |r_e(s, n)| = o(|n|^{-1-\delta}).\)

Proof. The case \(\delta > 0\) has been dealt with. Let \(\delta = 0\). As above we infer first that as \(|t| \vee |l| \to 0\),
\[
(3.3) \quad \int_{-\pi}^{\pi} |F(t, l)|\,dt = o(1/l), \quad \int_{-\pi}^{\pi} |\partial_tF(t, l)|\,dt = o(1/l^2),
\]
and then that \(\sup_s |r_e| = o(1/n)\) (use the first assertion of Lemma [11.2] of the Appendix; note that \(r_e\) is given by the ‘sine formula’ after integrating by parts).

For estimation of \(r_o\) we exploit the fact that \(\sin n\ell\) is an odd function of \(s\) and to this end put
\[
h(t, l) = \frac{\rho(t)}{2} \left[ \frac{1}{1 - \psi(t, l)} - \frac{1}{1 - \psi(t, -l)} \right] = \rho(t) \frac{iE[e^{iXt} \sin Yl]}{(1 - \psi(t, l))(1 - \psi(t, -l))}
\]
so that
\[
r_o = 2i \int_0^{\pi} \sin n\ell \,d\ell \int_{-\pi}^{\pi} e^{-ist} h(t, l) \,dt \quad \text{and} \quad \partial_l h(t, l) = \frac{i}{2} [F(t, l) - F(t, -l)].
\]
From \(EXY = \sigma_{12} = 0\) it follows that \(E[e^{iXt} \sin Yl] = o(|t| + l^2)\). Hence
\[
\int_{-\pi}^{\pi} e^{-ist} h(t, l) \,dt \to 0 \quad \text{as} \quad l \to 0
\]
uniformly in \(s\) and on integrating by parts,
\[
r_o = \frac{i}{n} \int_{\pi/2}^{\pi} \cos n\ell \,d\ell \int_{-\pi}^{\pi} [F(t, l) - F(t, -l)] e^{-ist} \,dt.
\]
Now the required estimate, i.e. \(\sup_s |r_o| = o(1/n)\), follows from (3.3) in view of Lemma [11.2].

Up to now we have shown (1.2), the first formula of Theorem 1.1.

The case \(|s| \geq |n|\). We must prove (2.12) and (2.13). For the proof of (2.12) we set
\[
g(t, l) = \rho(t) \left[ \frac{1}{1 - \psi(t, l)} - \frac{1}{1 - \psi(l)} \right],
\]
and then that \(\sup_s |g(s, n)| = o(|n|^{-1-\delta})\), according to the last assertion of Lemma [11.2] in the Appendix (with the roles of \(n\) and \(s\) reversed: the convergence in Lemma [11.2] is as \(s \to \infty\) and uniform in \(n\) in reverse to the present situation).
so that
\[ \rho(t) e_n(t) = \frac{1}{2\pi} \int_{-\pi}^{\pi} g(t, l) (e^{i nl} - 1) dl, \]
and we carry out elementary computations to see that for \( t \neq 0, \)
\[ \partial_t g(t, l) = \frac{\psi' \rho'}{(1 - \psi)} + \frac{(\psi - \phi) \rho'}{(1 - \psi)(1 - \phi)} \]
and
\[ \partial^2_t g(t, l) = \frac{(1 - \psi) \psi'' + 2[\psi'']^2 \rho}{(1 - \psi)^3} + \frac{2\psi' \rho'}{(1 - \psi)^2} + \frac{(\psi - \phi) \rho''}{(1 - \psi)(1 - \phi)}. \]
where a dash as well as of the periodicity of \( F \) and \( e \) because of a possible singularity at the origin, the outer integral must in
\[ (3.5) \]
Lemma 3.2.
It is easy to see (under the condition \( \delta > 0 \)) that \( \rho' \) is bounded, \( e_n(\pm 0) = 0 \) and \( e'_n(t) = o(1/t) \) as \( t \to 0 \) (which will be proved under \( \delta = 0 \) in Sections 4 and 5); in particular, \( (\rho e_n)'(\pm 0) = 0 \). Then, performing integration by parts with the help of this last relation as well as of the periodicity of \( \rho e_n \), we obtain
\[ \frac{1}{2\pi} \int_{-\pi}^{\pi} \rho(t) e_n(t) e^{-ist} dt = \frac{1}{4\pi^2 s^2} \int_{-\pi}^{\pi} (\rho e_n)'(t) e^{-ist} dt \]
(3.5)
\[ = -\frac{1}{4\pi^2 s^2} \int_{-\pi}^{\pi} e^{-ist} dt \int_{-\pi}^{\pi} \partial^2_t g(t, l)(e^{i nl} - 1) dl, \]
where because of a possible singularity at the origin, the outer integral must in general be understood to be an improper integral (which exists since the boundary values \( (\rho e_n)'(\pm 0) \) do).
Let \( w(t) \) be a smooth even function such that \( w = 1 \) in a neighborhood of 0 and \( w = 0 \) for \( |t| > 1 \) and set
\[ F_1(t, l) = w(t) \frac{2\sigma^2|t|}{Q(t, l)} \]
(3.6)
and make the decomposition
\[ \partial^2_t g(t, l) = F_1 + F_2 + F_3 \]
(3.7)
with
\[ F_2(t, l) = \frac{\rho''(t)}{1 - \psi(t, l)} - \frac{\rho''(t)}{1 - \phi(l)} \]
and \( F_3 \) being the rest, i.e. \( F_3 = \partial^2_t g(t, l) - F_1 - F_2 \); explicitly
\[ F_3 = \frac{\psi'' \rho}{(1 - \psi)^2} + \frac{2[\psi'']^2 \rho}{(1 - \psi)^3} + \frac{2\psi' \rho'}{(1 - \psi)^2} - w(t) \left( \frac{|t|}{Q} \partial_t^2 \frac{2\sigma^2}{Q^2} - \frac{8\sigma^2 \sigma^2 |t|}{Q^2} \right). \]
(3.8)
In the next section we obtain an explicit form of the contribution of \( F_1 \) (Lemma 4.1); according to it, the right side of (3.5) can be written as
\[ \frac{\lambda^2 |n|^3}{\pi ||(s, -n)||^2 s^2} - \frac{1}{4\pi^2 s^2} \int_{-\pi}^{\pi} e^{-ist} dt \int_{-\pi}^{\pi} (F_2 + F_3)(e^{i nl} - 1) dl + O(1/s^4). \]
(3.9)
Note that \( 2\sigma^2 |t|/Q(t, l) \) appearing in the definition of \( F_1 \) is the principal part of \( \rho/(1 - \psi) \).
Lemma 3.2. Let \( 0 \leq \delta < 1 \). Then as \( |s| \to \infty, \)
\[ \frac{1}{2\pi} \int_{-\pi}^{\pi} \rho(t) e_n(t) e^{-ist} dt = -\frac{\lambda^2 |n|^3}{\pi ||(s, -n)||^2 s^2} + o\left( \frac{n \log |s|}{|s|^2 + s} \right). \]
Proof. Let $\delta > 0$. In view of the formulae (3.5) and (3.9), it suffices to show that

$$I_k := \int_{-\pi}^{\pi} e^{-ist} dt \int_{-\pi}^{\pi} F_k(t, l)(1 - e^{int})dl = o\left( \frac{n \log |s|}{|s|^{\delta}} \right) \quad (k = 2, 3).$$

It follows that as $t - t' \to 0$ and $t^2 + l^2 \to 0$,

$$F_3(t, l) = \frac{|l|}{(Q(t, l))^2} \times o\left( |t|^{\delta} + |l|^{\delta} \right)$$

and

$$|F_3(t, l) - F_3(t', l)| = \frac{|t - t'|}{(Q(t, l))^2} \times o\left( |t|^{\delta} + |l|^{\delta} \right) + \frac{1}{(Q(t, l))^{3/2}} \times o\left( |t - t'|^{\delta} \right).$$

According to Lemma 11.4 (with $\omega = (1,0)$) of Appendix (B), these bounds together yield the required estimate of $I_3$, provided $\delta > 0$.

$I_2$ is estimated in a similar way (if $\delta > 0$): write $I_2 = 2\pi \int e^{-ist}\rho'(t)\rho_n(t)dt$, observe that $|\rho_n(t)|$ and $|\rho_n'(t)|$ are uniformly bounded by a constant times $|n|$ (we shall give more detailed estimates for both of them in Section 5) and apply the estimates concerning $\rho''$ given in Lemma 4.2 of Section 4 and you will find the required estimate of $I_2$ in view of Lemma 11.3 (with $d = 1$). The case $\delta = 0$ is dealt with at the very end of this section. $\square$

The proof of (2.12) is similar but only simpler: one has only to observe that

$$\int_{-\pi}^{\pi} |t|w(t)e^{-ist}dt = 2 \int_0^\pi tv(t) \cos st \, dt = -2s^{-2} + O(s^{-N})$$

for every $N > 0$ and

$$\int_{-\pi}^{\pi} \left( \rho(t) - \sigma^2 |t|w(t) \right)e^{-ist}dt = o\left( \frac{\log |s|}{|s|^{2+\delta}} \right).$$

In the case $\delta > 0$ the latter is obtained by applying Lemmas 4.2 and 11.4 as in the proof of Lemma 3.2. If $\delta = 0$, we integrate once by parts the above integral and then split the range of the resulting integral at $t = \pm 1/|s|$. The integral on $|t| < 1/|s|$ is $O(1/s^2)$ since $\rho'$ is bounded and the other on $|t| \geq 1/s$ is $o((\log |s|)/s^2)$ owing to $\rho'' = o(1/t)$ (Lemma 11.4). Thus (2.12) has been verified.

For the proof of Lemma 3.2 in the case $\delta = 0$ we can proceed as in the argument just made above (namely we prove that $\int_{|t|<1/s}(\rho \rho_n)'e^{-ist}dt = O(1/s)$ and $\int_{|t|\geq1/s}(\rho \rho_n)'e^{-ist}dt = o((\log |s|)/s^2)$ of which the details will be found in the beginning of Section 6; see (6.2) and a similar estimate for $F_1$ given after it). This completes the proof of Lemma 3.2 and hence the proof of Theorem 1.1.

4. Lemmas on $F_1(t,l)$ and $\rho(t)$

In this section we prove two lemmas that have been applied in the second half of the preceding section, of which all the arguments given in this section are independent. Recall it is supposed that $Q$ is diagonal (so that $\lambda = \sigma^2/\sigma_2^2 = \sigma_1/\sigma_2$).

The first lemma concerns the function

$$F_1(t, l) = w(t)\partial_t^2 \left[ \frac{2\sigma^2|t|}{Q(t, l)} \right] = w(t) \frac{(at^2 + bl^2)|t|}{(Q(t, l))^{\delta}} \quad (t \neq 0),$$

where $a = 4\sigma_1^2\sigma^2$ and $b = -12\sigma^6$ (these values of $a, b$ are of no significance in what follows).
Lemma 4.1. Uniformly in $n$, as $|s| \to \infty$,
\[
\frac{1}{4\pi^2 s^2} \int_{-\pi}^{\pi} e^{-ist} dt \int_{-\pi}^{\pi} F_1(t,l)(e^{int} - 1) dl = \frac{\lambda^2 |n|^3}{\pi \| (s, -n) \|^2 s^2} \frac{2}{3} + O \left( \frac{1}{s^4} \right).
\]

Proof. Let $n > 0$. Twice differentiate both sides of the identity
\[
\int_{-\pi}^{\pi} 2\sigma^2 |t| (e^{int} - 1) dl = 2\pi e^{-\lambda n|t|} - 2\pi - \int_{-\pi}^{\infty} 4\sigma^2 |t| Q(t,l) (\cos nl - 1) dl
\]
and multiply by $w(t)$ the obtained derivatives, and you find
\[
(4.1) \quad \int_{-\pi}^{\pi} F_1(t,l)(e^{int} - 1) dl = 2\pi (\lambda n)^2 e^{-\lambda n|t|} w(t) - 2 \int_{-\pi}^{\pi} F_1(t,l)(\cos nl - 1) dl \quad (t \neq 0).
\]

Observe that
\[
\int_{-\pi}^{\pi} e^{-ist} F_1(t,l) dt = -[2be^2/|Q(0,l)|^3 s^2] + O(1/s^3 t^2) \quad (|s|, |l| \to \infty),
\]
and then deduce that as $s \to \infty$,
\[
\frac{1}{4\pi^2} \int_{-\pi}^{\pi} e^{-ist} dt \int_{-\pi}^{\pi} F_1(t,l)(e^{int} - 1) dl = \frac{\lambda^2 n^3}{\pi \| (s, -n) \|^2} - 4\pi (\lambda n)^2 \int_{0}^{\infty} [1 - w(t)] e^{-\lambda nt} \cos st dt + O \left( \frac{1}{s^2} \right),
\]
which, the last integral being $O(|s|^{-N})$ (since $n^{N+2} \int_{0}^{\infty} (1 - w)e^{-\lambda nt} dt$ is bounded), shows the asymptotic formula of the lemma. □

Remark 3. For $n \neq 0$ the asymptotic formula of Lemma 4.1 is valid and unaltered even if $e^{int}$ replaces $e^{int} - 1$. It is noted however that for the derivation of $\hat{\rho}''$, the factor $e^{int} - 1$ plays a significant role and cannot be replaced by $e^{int}$.

Lemma 4.2. (i) As $t \to \pm 0$,
\[
\rho(t) = \sigma t + o(t^{1/2}), \quad \rho'(t) = \pm \sigma^2 + o(|t|^{1/2}) \quad \text{and} \quad \rho''(t) = o(|t|^{1-1}).
\]
(ii) For $|t_1| < |t_2|$, as $t_1 - t_2 \to 0$,
\[
|\rho''(t_1) - \rho''(t_2)| = o \left( \frac{|t_1 - t_2|}{|t_1|} \right) + o \left( \frac{|t_1 - t_2|^3}{|t_1|^3} \right).
\]
(iii) If $\hat{\rho''}(t) = \rho''(t) - \zeta(t)$, where
\[
\zeta(t) = -\frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} \frac{\partial^2 \psi}{(1 - \psi)^2} d\ell,
\]
then $\hat{\rho}''$ is differentiable for $t \neq 0$ and $\hat{\rho}''(t) = o(|t|^{3/2})$ as $t \to 0$.

Proof. The first estimate of (i) is the same as \textit{(2.6)}. Similarly to the verification of it one deduces $\pi_0''(t) = -\sigma^2 t + o(|t|^{1/2})$, and substitution from it as well as from $\rho(t) = \sigma t + o(|t|^{1/2})$ into $\rho' = -\rho^2 \pi_0$ gives the desired estimate of $\rho'$.

For verification of the rest of the lemma, observe that
\[
\rho'' = \frac{2(\rho')^2}{\rho} - \rho^2 \pi_0'' \quad \text{and} \quad \pi_0'' = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{\psi''}{(1 - \psi)^2} d\ell + \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{2|\psi'|^2}{(1 - \psi)^3} d\ell,
\]
where $\psi' = \partial_t \psi$ and $\psi'' = \partial_t^2 \psi$. Then as above we see that $\rho^2 \pi_0'' = 2(\rho')^2/\rho = 2\sigma^2/|t|^{-1}(1 + o(1))$ as $t \to 0$; hence $\rho''(t) = o(|t|^{-1})$. (The symbol $\sim$ means that the ratio of the two sides tends to unity.) Put

$$\theta(t) := \frac{2\rho^2}{\sigma^2|t|^3} + \frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} \frac{\sigma^2}{(Q/2)^3} dl - \frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} \frac{2(\sigma^2 t)^2}{(Q/2)^3} dl,$$

so that

$$\dot{\rho}''(t) - \theta(t) = \frac{2(\rho')^2}{\rho} - \frac{2\rho^2}{\sigma^2|t|^3} + \frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} \left( \frac{2|\psi'|^2}{(1-\psi)^3} - \frac{2(\sigma^2 t)^2}{(Q/2)^3} \right) dl$$

$$+ \frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} \left( \frac{1}{(1-\psi)^2} - \frac{1}{(Q/2)^2} \right) E[X^2 e^{itY}] dl$$

$$+ \frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} E[X^2 (e^{itY} - 1)] dl.$$

With the help of the estimates

$$\psi'' = -\sigma_t^2 + o(|t|^\delta + |t|^\delta), \quad \psi' = -\sigma_t^2 t + o(|t|^{1+\delta} + |t|^{1+\delta}),$$

each an application of Lemma 2.3 shows that both $\zeta(t)$ and $\dot{\rho}''(t) - \theta(t)$ are $o(|t|^{\delta-1})$. In particular, it follows that $\dot{\rho}''(t) = o(1/\rho)$; hence $\theta(t) = o(1/\rho)$, which in turn implies $\theta(t) = O(1)$ and $\dot{\rho}'(t) = \theta(t)$ since $|t|^3 \theta(t)/\rho^2(t)$ is ‘analytic’ in $|t|$. Consequently $\rho''(t) = o(|t|^\delta-1)$. Similarly we obtain $\dot{\rho}''(t) = o(|t|^\delta-2)$.

If $h_i(t) = \psi''(t,i), then h_i(t) - h_i(t') = o(|t - t'|^\delta)$ uniformly in $t$, and we deduce that $\zeta(t)$ satisfies the property (1.2) in place of $\rho''$. In view of the estimate $\dot{\rho}''(t) = o(|t|^{\delta-2}), the function $\dot{\rho}''$ also satisfies the same property without the second term on the right side of (1.2). Thus (1.2) is verified. \hfill \Box

5. Estimation of $e_n(t)$

In this section we consider the case $\delta = 0$ only. The results obtained in this section will be used in Sections 6, 7 and 8. Set

$$\left\{ \begin{array}{l}
\kappa_n(t) = \frac{1}{2\pi n} \int_{-\pi}^{\pi} \left[ \frac{1}{1 - \psi(t,l)} - \frac{1}{1 - \phi(l)} \right] \left\{ \cos nl - 1 \right\} dl \\
\lambda_n(t) = \frac{1}{2\pi n} \int_{-\pi}^{\pi} \left[ \frac{1}{1 - \psi(t,l)} - \frac{1}{1 - \phi(l)} \right] \left\{ \sin nl - 1 \right\} dl,
\end{array} \right.$$

so that $e_n(t)/n = \kappa_n(t) + ih_{-n}(t)$. Recall that $e_n(t) = x_n(t) - \pi_0(t) + o(n)$.

**Lemma 1.** Put $f(x) = |x|^{-1}(e^{-|x|} - 1) + 1 = \frac{1}{2} |x| - \frac{1}{2} |x|^2 + \cdots$ and define $r_n(t)$ via

$$\kappa_n(t) = \sigma_t^2 f(\lambda n t) + r_n(t).$$

Then, $r_n(t) = o(nt)$ as $nt \to 0$ and

$$\lim sup_{t \to 0} |r_n(t)| = \lim_{n \to \infty} sup_{t} |r_n(t)| = 0,$$

and these same estimates hold true both for $|t|r_n'(t)$ and for $t^2 r_n''(t)$ in place of $r_n(t)$.

**Proof.** By $E[XY] = 0$ we have $\psi(t,l) - \phi(l) = -\frac{1}{2} \sigma_t^2 t^2 + t \times o(|t| + |l|)$ and hence

$$\frac{\psi - \phi}{(1 - \psi)(1 - \phi)} = \frac{-2t^2}{Q(t,l)} = \frac{t \times o(|t| + |l|)}{(t^2 + l^2)^2}.$$
as $|t| \vee |l| \to 0$. The required estimate of $r_n(t)$ follows from
\[
\frac{1}{n\pi} \int_0^\pi \frac{-2\lambda^2 t^2}{Q(t,l)^2} (\cos nl - 1) dl = \frac{1}{n\pi} \int_0^\pi dt \int_0^\pi \frac{2\lambda^2 t^2}{Q(t,l)} \cdot \frac{\sin tl}{l} dl
\]
\[
= e^{-\lambda nt} - 1 + \lambda nt \quad \sigma_2^2 \lambda t + O(t^2/n).
\]
The estimates of $|t|r_n'(t)$ are obtained by simply observing that the derivative with respect to $t$ of the left side of (5.1) is $o(|t| + \pi)/(t^2 + l^2)$ (make a telescopic decomposition of the difference of two ratios in (5.1)). The second derivative is treated similarly. \qed

The next lemma is an immediate corollary of the preceding lemma.

**Lemma 5.2.** Uniformly in $n \geq 1$ and $|t| < \pi$,
\begin{enumerate}[(i)]
\item $|h_n^2(t)| \simeq |nt| \land 1$ (namely, $C^{-1}(|nt| \land 1) \leq |h_n^2(t)| \leq C(|nt| \land 1)$ for some constant $C > 0$);
\item $|t(h_n^3)'(t)| \simeq |nt| \land 1$.
\end{enumerate}

**Lemma 5.3.**
\[
\lim_{n \to \infty} \sup_{t} \left| \int_{-\pi}^\pi \frac{1}{1 - \psi(t,l)} \frac{\sin nl}{n} dl \right| = 0.
\]
Moreover
\[
\lim_{t \to 0} \sup_{n} |h_n^3(t)| = \lim_{n \to \infty} \sup_{t} |h_n^3(t)| = 0.
\]

**Proof.** Denote by $I = I(t,n)$ the integral appearing in (5.2). Then
\[
I = \int_{-\pi}^\pi \frac{iE[e^{itX} \sin Y]}{(1 - \psi(t,l))(1 - \psi(t,-l))} \frac{\sin nl}{n} dl.
\]
Since $E[X] = 0$, we can write
\[
E[e^{itX} \sin Y] = E[e^{itX} (\sin Y - lY)] = E[(e^{itX} - 1 - itX)Y]|t|
\]
correspondingly we decompose $I = I_1 + I_2$. In view of the integrability
\[
\int_{-\pi}^\pi \frac{E[\sin Y - lY]}{|l|^3} dl = E \left[ \int_{-\pi}^\pi \frac{\sin u - u}{|u|^3} du \left| \frac{Y}{2} \right| \right] < 4E[Y^2] < \infty,
\]
the dominated convergence theorem shows that $I_1$ converges to zero as $n \to \infty$ uniformly in $t$; moreover it also follows that
\[
I_1 \to \int_{-\pi}^\pi \frac{1}{1 - \psi(t,l)} \frac{\sin nl}{n} dl
\]
as $t \to 0$ uniformly in $n$. The second part $I_2$ converges to zero as $n \to \infty$ uniformly in $t, \varepsilon < |t| \leq \pi$ for every $\varepsilon > 0$, but in the inequality
\[
|I_2| \leq C \frac{E[(e^{itX} - 1 - itX)Y]}{|t|} \int_{-\pi}^\pi \frac{|t|^2}{(t^2 + l^2)^2} \frac{\sin nl}{|nl|} dl,
\]
the integral on the right side is uniformly bounded and the fraction before it approaches zero as $t \to 0$, so that the convergence as $n \to \infty$ is uniform in $|t| \leq \pi$. These show the three assertions of the lemma simultaneously. \qed

**Lemma 5.4.** $\lim_{t \to 0} \sup_{n} |t(h_n^3)'(t)| = 0$ and $\lim_{t \to 0} \sup_{n} |t^2(h_n^3)''(t)| = 0$. 
Proof. For the proof of the first half it suffices (owing to skew symmetry in \( l \)) to verify that as \( t \to 0 \),
\[
\int_{-\pi}^{\pi} \left| E[X e^{iX t + i Y l}] \right| \cdot \left| \frac{1}{(1 - \psi)^2} - \frac{4}{Q^2} + \frac{4|E[X e^{iX t} \sin Y l]|}{|Q(t, l)|^2} \right| |t|dl \to 0.
\]
But this follows from Lemma 2.3 since \( E[X e^{iX t} \sin Y l] = o(|l|) \) and \( E[X e^{iX t + i Y l}] = O(|t| + |l|) \) as \( |t| + |l| \to 0 \). The proof of the second one is similar.

As a consequence of Lemmas 5.1, 5.3 and 5.4 we have

**Lemma 5.5.** If \( f(x) = |x|^{-1}(e^{-|x|} - 1) + 1 \), then
\[
e_n(t)/|n| = \sigma_n^{-2}f(\lambda t) + h_n(t)
\]
with \( r_n(t) + h_n(t) \), \( t(r_n + h_n')'(t) \) and \( t^2(r_n + h_n'')'(t) \) approaching zero as \( t \to 0 \) uniformly in \( n \). In particular each of \( e_n(t)/|n| \), \( te_n'(t)/|n| \) and \( t^2e_n''(t)/|n| \) tends to zero as \( nt \to 0 \) and are uniformly bounded.

In the next section we apply the result of this section only for (6.2). It is noted that we shall deal with the derivatives \( e_n(t) \), \( e_n'(t) \) implicitly in the estimation of the integral of \( F_3 \) through the identity
\[
\frac{1}{2\pi} \int_{-\pi}^{\pi} F_3(t, l)(1 - e^{inl})dl = \rho(t)e_n(t) + 2\rho'(t)e_n'(t) - \frac{1}{2\pi} \int_{-\pi}^{\pi} F_1(t, l)(1 - e^{inl})dl,
\]
wherein we shall need to look more closely at these derivatives in relation to the corresponding parts involved in the last integral above.

**6. Proof of Theorem 1.2**

We are to evaluate \( H_n(s) \) for \( |s| > |n| \) under the condition (1.6), i.e. under \( E[X^2 \log |X|] < \infty \). Let \( g, F_1, F_2 \) and \( F_3 \) be the functions defined in (3.4) and (3.7). Because of a possible singularity at the origin we separate
\[
\eta_{n,s} := \frac{1}{4\pi^2} \int_{|t|<\alpha/|s|} e^{-ist} dt \int_{-\pi}^{\pi} \partial_t^2 g(t, l)(e^{inl} - 1)dl
\]
from the integral on the right side in (3.9) and write the latter as
\[
\frac{1}{2\pi} \int_{-\pi}^{\pi} \rho(t)e_n(t)e^{-ist}dt
\]
\[
= \frac{-1}{4\pi^2 s^2} \int_{\alpha/|s|<|t|<\pi} e^{-ist} dt \int_{-\pi}^{\pi} \partial_t^2 g(t, l)(e^{inl} - 1)dl - \frac{\eta_{n,s}}{s^2}.
\]
Recalling \( \int \partial_t g(e^{inl} - 1)dl = 2\pi(\rho e_n)' \), one integrates by parts back and uses Lemma 5.5 to find that
\[
\frac{1}{n} \eta_{n,s} \to 0 \quad \text{as} \quad |s| \to \infty \quad \text{and} \quad \alpha \downarrow 0 \quad \text{in this order uniformly for} \quad |n| < |s|.
\]
In the same limit we have also \( \int_{|t|<\alpha/|s|} e^{-ist} dt \int_{-\pi}^{\pi} F_1(t, l)(e^{inl} - 1)dl \to 0 \) and, in view of (3.9),
\[
H_n(s) = a^*(n)H_0(s) - \frac{\lambda^2 |n|^3}{\pi ||(s, n)||^2 s^2}
\]
\[
- \frac{1}{4\pi^2 s^2} \int_{\alpha/|s|<|t|<\pi} e^{-ist} dt \int_{-\pi}^{\pi} (F_2 + F_3)(e^{inl} - 1)dl + o\left( \frac{n}{s^2} \right).
\]
Our task for the rest of the proof consists of proving that for each \( \alpha > 0 \),

\[
\lim_{s \to \infty} \sup_{|n| < s} \frac{1}{n} \int_{\alpha/s < |t| < \pi} e^{-ist} dt \int_{-\pi}^{\pi} (F_2 + F_3)(e^{int} - 1) dl = 0
\]

and of obtaining a correct asymptotic form of \( H_0 \). For both purposes we shall make use of the assumption (1.6), which will be applied via the following lemma.

**Lemma 6.1.** The integral \( \int_{[-\pi, \pi]^2} \frac{E[X^2(1 - \cos tX)]}{l^2 + t^2} dt dl \) is finite if and only if \( E[\log^2 |X|] < \infty \); if this is the case, then \( \int_{[-\pi, \pi]^2} \frac{E[X^2|1 - e^{itX}]}{l^2 + t^2} dt dl < \infty \).

**Proof.** The integral \( \int_{[-\pi, \pi]^2} \frac{(1 - \cos tX)1(|t| < 1)}{l^2 + t^2} dt dl \) is dominated by

\[
\int_{-\pi}^{\pi} \frac{1}{|t| < 1} \left[ \frac{C}{|t|} \right] dt dl \leq 4 \int_{0}^{\infty} \int_{0}^{1} \frac{udu}{u^2 + v^2} < \infty,
\]

while the same integral but on \(|t| \geq 1\) equals

\[
41(|X| \neq 0) \int_{1/|X|}^{\pi} \frac{1 - \cos tX}{t} dt \int_{0}^{\pi/t} \frac{du}{1 + u^2} \sim C \log |X|
\]

as \(|X| \to \infty\) (with \( C = 4 \int_{0}^{\infty} (1 + u^2)^{-1} du \)). Thus the equivalence of the first half of the lemma follows. The second half is proved by the same argument that has just been advanced. \( \square \)

Now we proceed with the evaluation of \( H_0 \), in which we need to cope with the delicate circumstance that there is little information available as to the regularity of \( \rho'' \) other than \( \rho''(t) = o(1/t) \). For simplicity let \( s > 0 \) in the rest of this section.

**Evaluation of \( H_0 \).** Recalling \( 2\pi H_0(s) = -\int_{-\pi}^{\pi} \rho(t)e^{-ist} dt \) we directly derive

\[
2\pi s^2 H_0(s) = is \int_{|t| < \alpha/s} \rho'(t)e^{-ist} dt + \int_{\alpha/s < |t| < \pi} \rho''(t)e^{-ist} dt
\]

independently of the arguments made above. From the relation \( \rho' = \sigma^2 t/|t| + o(1) \) it follows that as \( s \to \infty \) and \( \alpha \downarrow 0 \) in this order, the first term converges to zero and the second one to \( 2\sigma^2 \). For the derivation of the desired estimate of \( H_0 \) we must prove that for each \( \alpha > 0 \),

\[
\lim_{s \to \infty} \int_{\alpha/s < |t| < \pi} \rho''(t)e^{-ist} dt = 0.
\]

For the proof we make use of the decomposition of \( \rho'' \) in Lemma 1.2

\[
\rho''(t) = \tilde{\rho}''(t) + \zeta(t), \quad \text{where} \quad \zeta(t) = -\frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} \frac{\partial^2 \psi}{(1 - \psi)^2} dl.
\]

Note that \( \tilde{\rho}'' \) is differentiable for \(|t| > 0\), while \( \zeta(t) \) may not be. In any case we have

**Lemma 6.2.** (i) \( \int_{-\pi}^{\pi} |\zeta(t)| dt < \infty \) if \( E[\log^2 |X|] < \infty \) and (ii) \( \tilde{\rho}''(t) = o(|t|^{-2}) \) as \( t \to 0 \).
Remark to Lemma 6.2. One can show that \( \int_{-\pi}^{\pi} |\rho''(t)| \, dt < \infty \) if \( E[X^2 \log |X|] < \infty \), which is useful but dispensable; we shall need to use the second assertion of the lemma in several places.

The proof of (6.5) is now given as follows. The integrability of \( \zeta(t) \) implies that its contribution vanishes in the limit under consideration and that the improper integral \( \int_{\pi}^{\pi} \tilde{\rho}'' \, dt \) exists. On using the latter fact together with the bound \( \tilde{\rho}'' = o(1/t^2) \), the contribution of \( \tilde{\rho}'' \) also vanishes (see Lemma 11.2 of the Appendix).

We can thus conclude that \( H_0(s) = \pi^{-1} \sigma^2 s^{-2} (1 + o(1)) \) under \( E[X^2 \log |X|] < \infty \).

We turn to the proof of (6.3). First consider the contribution of \( F_3 \) to the double integral in (6.3) and break it into two parts:

\[
\Theta_1 = \int_{\alpha/s < |t| < \pi} e^{-ist} dt \int_{-\pi}^{\pi} \left[ l^2 F_3(t, l) \right] \frac{1 - \cos nl}{l^2} \, dl,
\]

\[
\Theta_{11} = \int_{\alpha/s < |t| < \pi} e^{-ist} dt \int_{-\pi}^{\pi} \left[ lF_3(t, l) \right] \sin nl \, dl.
\]

We have

\[
|F_3| \leq \frac{|t|}{|Q(t, l)|^2} c(t, l)
\]

with \( c(t, l) \) bounded and \( c(t, l) \to 0 \) \((|t| + |l| \to 0)\) and, making use of this, we infer that \( \Theta_1 = n \times o(1) \) as \( s \to \infty \) (see Lemma 11.1 of the Appendix). The corresponding estimate of \( \Theta_{11} \) requires the condition (1.6).

Lemma 6.3. If \( E[X^2 \log |X|] < \infty \), then \( \Theta_{11} / n \to 0 \) as \( |s| \to \infty \) uniformly in \( n \).

Proof. Put

\[
h(t, l) = \rho(t) \frac{\partial^2 \psi(t, l) + E[X^2 e^{iY}]}{(1 - \psi(t, l))^2}
\]

and

\[
f_n(t) = \int_{-\pi}^{\pi} \left[ lF_3(t, l) - lh(t, l) \right] \frac{\sin nl}{nl} \, dl,
\]

so that

\[
\Theta_{11} = \int_{\alpha/s < |t| < \pi} e^{-ist} dt \int_{-\pi}^{\pi} lh(t, l) \cdot \frac{\sin nl}{nl} \, dl + n \int_{\alpha/s < |t| < \pi} e^{-ist} f_n(t) \, dt.
\]

As before, \( f_n(t) \) is differentiable for \( t \neq 0 \) while \( h(\cdot, l) \) may not be. On the same basis for Lemma 6.2 one verifies that

(i) \( \int_{|t| < \pi} |lh(t, l)| \, dt \, dl < \infty \) if \( E[X^2 \log |X|] < \infty \) and

(ii) \( \sup_n |f_n(t)| = o(|t|^{-1}) \) and \( \sup_n |f_n'(t)| = o(|t|^{-2}) \) as \( t \to 0 \).

Taking these into account, we make use of Lemmas 11.1 and 11.2 of the Appendix for the first and the second terms, respectively, to conclude that \( \Theta_{11} = n \times o(1) \).

It remains to deal with the contribution of \( F_2 \) in (6.3). Suppose \( E[X^2 \log^+ |X|] < \infty \). Put

\[
F_{21} = \frac{\rho''(t)}{1 - \psi(t, l)} \quad \text{and} \quad F_{22} = \frac{\rho''(t)}{1 - \phi(l)}.
\]
so that $F_2 = F_{21} - F_{22}$. In the evaluation of $H_0$ made above we have verified that
\[
\int_{\alpha<s<|t|<\pi} e^{-ist} dt \int_{|t|<\pi} F_{22}(1 - e^{inl}) dl = 2\pi a(n) \int_{\alpha<s<|t|<\pi} \rho''(t) e^{-ist} dt
\]
(6.9)

In a similar way the integral involving $F_{21} \sin nl$ is estimated to be $n \times o(1)$ in view of (6.2).

Finally we work with $F_{21}(1 - \cos nl)$. We make the decomposition $\rho'' = \overset{\text{even}}{\rho''} + \overset{\text{odd}}{\rho''}$ in (6.6). On the one hand the integrability of $\overset{\text{odd}}{\rho''}$ (Lemma 6.3 (i)) implies, by dominated convergence, that $\int_{-\pi}^{\pi} |\overset{\text{odd}}{\rho''}(t)| \cdot |1 - \psi|^{-1} dt = o(1/l^2)$ as $l \to 0$, and hence the contribution of $\overset{\text{odd}}{\rho''}$ is $n \times o(1)$ in view of Lemma 11.1. On the other hand, noting that for some constant $C$, we apply Lemma 11.2 to see that the contribution of $\overset{\text{even}}{\rho''}$ is $n \times o(1)$. We accordingly conclude that $\int_{\alpha<s<|t|<\pi} e^{-ist} dt \int_{-\pi}^{\pi} F_{21}(1 - \cos nl) dl = n \times o(1)$ for each $\alpha > 0$ as required.

The proof of (6.3) is now complete. Summarizing the results obtained above we have

**Proposition 6.4.** If $E|X^2 \log |X|| < \infty$, then uniformly for $n < |s|$, as $|s| \to \infty$,
\[
\frac{1}{2\pi} \int_{-\pi}^{\pi} \rho(t)e_n(t)e^{-ist} dt = -\frac{\sigma^2}{\pi} \cdot \frac{|n|^3}{\|(s, n)\|^2 s^2} + n \times o(1).
\]

Combined with (2.11) and the estimate of $H_0(s)$ already obtained, this formula yields
\[
H_n(s) = \frac{\sigma^2 a^*(n)}{\pi\|(s, n)\|^2} (1 + o(1)) \ (|s| > n),
\]
which together with the first half of Theorem 1.1 finishes the proof of Theorem 1.2 (in view of the asymptotic form of $a(n)$ as mentioned in Remark 1 (i)).

### 7. Proof of Theorem 1.3

Let $s > 0$ throughout this section. First consider $H_0$. The proof starts from the expression of $2\pi s^2 H_0(s)$ given in (6.4). The sum of the first two terms of it equals
\[
\left[\rho'(t)e^{-ist}\right]_{t=-\alpha/s}^{\alpha/s} + is \int_{|t|<\alpha/s} \rho'(t)e^{-ist} dt = 2\sigma^2 + \int_{|t|<\alpha/s} \rho''(t)e^{-ist} dt.
\]
But
\[
\int_{|t|<\alpha/s} \rho''(t) dt = [\rho'(\alpha/s) - \sigma^2] + [-\sigma^2 - \rho'(-\alpha/s)] = 0
\]
and $\int_{|t|<\alpha/s} |\rho''(t)(e^{-ist} - 1)| dt \to 0$ as $s \to \infty$ locally uniformly in $\alpha$, so that
\[
2\pi s^2 H_0(s) = 2\sigma^2 + \int_{\alpha/s<|t|<\pi} \rho''(t)e^{-ist} dt + o(1),
\]
where $o(1) \to 0$ as $s \to \infty$ for each $\alpha > 0$. Thus, on letting $\alpha = 1$, the assertion of Theorem 3 (for $n = 0$) may be paraphrased as
\[
\int_{|t|<\pi} \rho''(t)e^{-ist} dt = \frac{2}{\lambda} M_\varepsilon(s)(1 + o(1)) + o(1).
\]
Recall \((6.6)\), i.e., the decomposition \(\rho'' = \bar{\rho}' + \zeta\) made in (iii) of Lemma \([1,2]\) where we have observed that \(\int_{1/s<|t|<\pi} \bar{\rho}'(t)e^{-ist}dt \to 0\) (under the existence of the second moment only); hence \((7.2)\) is reduced to
\[
(7.3) \quad J(s) := \int_{1/s<|t|<\pi} \zeta(t)e^{-ist}dt = \frac{2}{\lambda}M_{\varepsilon}(s)(1 + o(1)) + o(1).
\]
The proof of this relation is given below, of which the method is the same as one devised in \([9]\) for similar formulae.

We write
\[
\zeta(t) = \frac{\rho^2(t)}{2\pi} \int_{-\pi}^{\pi} E[X^2e^{itY}(e^{itX} - 1)] \frac{dt}{(1 - \psi(t, l))^2}
\]
and decompose \(\zeta = \zeta_0 + \zeta_1 + \zeta_2\), where
\[
\zeta_0(t) = \frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} E[X^2e^{itY}(1 - w(Xt))] \frac{dt}{(1 - \psi)^2}
\]
\[
\zeta_1(t) = \frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} E[X^2e^{itY}(1 - w(Xt))] \frac{dt}{(1 - \psi)^2}
\]
\[
\zeta_2(t) = \frac{\rho^2}{2\pi} \int_{-\pi}^{\pi} E[X^2e^{itY}(e^{itX} - 1)w(Xt)] \frac{dt}{(1 - \psi)^2}
\]
Here \(w\) is a smooth function introduced just prior to \([3,6]\). We may suppose that \(w(t) = 1\) for \(|t| < 1/2\).

Similarly to the proof of Lemma \([6,1]\) we see that
\[
\int_{-\pi}^{\pi} |\zeta_2(t)| dt \leq C \int_{0}^{1} du \int_{0}^{\infty} \frac{u^2|e^{iu} - 1|}{(u^2 + v^2)^2} dv < \infty,
\]
which in view of the Riemann-Lebesgue lemma implies that
\[
(7.4) \quad \int_{1/s<|t|<\pi} \zeta_2(t)e^{-ist}dt = o(1).
\]
Note that \(|w'(Xt)Xt|\) as well as \(1 - w(Xt)\) is bounded by a constant times the indicator function \(1_{\{|X| > 1/2\}}\). On observing that \(\zeta_1(t) = o(1/t)\) and \(\zeta_1(t) = o(1/t^2)\), an integration by parts gives
\[
\int_{1/s<|t|<\pi} \zeta_1(t)e^{-ist}dt = 0(1).
\]

We are left with \(\zeta_0\). Split the range of integration into three parts according as \(|X - s| \geq \varepsilon s\), \(|X - s| < \varepsilon s\) or \(X = s\) and call \(J_1\), \(J_2\) and \(J_3\), respectively, their contributions to \(\int_{1/s<|t|<\pi} \zeta_0(t)e^{-ist}dt\). We then integrate by parts with respect to \(t\) by factoring the integrand as \(e^{it(X-s)}\times\)(the other) to deduce that for each \(\varepsilon > 0\), as \(s \to \infty\),
\[
|J_1| = \frac{1}{2\pi} \left| \int_{1/s<|t|<\pi} \rho^2 dt \int_{-\pi}^{\pi} E[X^2e^{it(X-s)}(1 - w(Xt))e^{itY}; |X - s| \geq \varepsilon s] \frac{dt}{(1 - \psi)^2} \right|
\]
\[
\leq CE\left[ \frac{sX^2}{|X - s|}; |X - s| \geq \varepsilon s, |X| \geq \frac{s}{2} \right] + C \int_{1/s}^{\pi} E\left[ \frac{X^2}{|X - s|}; |X - s| \geq \varepsilon s, |X| \geq \frac{1}{2t} \right] \frac{dt}{t^2} \to 0.
\]
For the inequality above we have made use of the relations \( \rho(\pi) = \rho(-\pi), \) \( w(\pm X\pi) = 1 \) for \( X \neq 0, \) \( s^{-2} \int_{\pi}^{\infty} (s^{-2} + t^2)^{-2} \, dl = O(s) \) and \( t \int_{\pi}^{\infty} (t^2 + 1)^{-2} \, dl = O(1/t^2). \)

We may suppose that \( \varepsilon < \frac{1}{4} \) and \( w(x) = 0 \) if \( |x| \geq 3/4, \) so that in the event \( |X - s| < \varepsilon s, \) \( 1 - w(Xt) = 1 \) for \( |t| \geq 1/s. \) Taking this into account we write \( J_2 \) in the form

\[
J_2 = E \left[ X^2 \int_{1/s < |t| < \pi} \frac{e^{it(X-s)}}{|t|} h(t) \, dt; \ 1 \leq |X - s| < \varepsilon s \right],
\]

where

\[
h(t) = h(t, Y) = \frac{1}{2\pi} \int_{-\pi}^{\pi} |t| e^{itY} \, dY.
\]

Split the range of the integral under the expectation symbol in \( (7.5) \) according as \( |(X-s)t| > 1 \) or \( |(X-s)t| \leq 1 \) and call \( J_{21} \) and \( J_{22} \) the corresponding parts of \( J_2. \)

By integration by parts,

\[
|J_{21}| \leq E \left[ X^2 \int_{1/|X-s| < |t| < \pi} \left| \int_t^{(\text{sign} \, t)\infty} \frac{e^{i(X-s)u}}{|u|} du \right| h'(t) \, dt; \ 1 \leq |X - s| < \varepsilon s \right] + o(1),
\]

where \( \text{sign} \, t = t/|t|. \) Since \( \int_{|t|}^{\infty} e^{\pm i|X-s|u} u^{-1} \, du \leq C/(|X-s|t) \) and \( |h'(t)| \leq C/|t|, \) the outer integral under the expectation is bounded; hence \( J_{21} \) is \( o(1) \) (as \( s \to \infty). \)

For the evaluation of \( J_{22} \) we further decompose it into three parts in the same way as we did \( J \) but by means of \( Y \) in place of \( X - s \) and call \( J_{221}, J_{222} \) and \( J_{223} \) those that correspond to \( |Y| \geq \varepsilon s, \) \( 0 < |Y| < \varepsilon s \) and \( Y = 0, \) respectively. The same method that is applied to \( J_1 \) verifies \( J_{221} = o(1). \) In what follows we prove that the remaining parts, i.e., \( J_{222}, J_{223} \) and \( J_3, \) together constitute \( M_c(s). \) For simplicity we consider the double integral involved in \( J_{222} \) only on the first quadrant \( t > 0, l > 0, \) and let \( \tilde{J}_{222} \) denote the corresponding one-fourth of it, so that

\[
\tilde{J}_{222} = \frac{1}{2\pi} E \left[ X^2 \int_{1/s}^{1/|X-s|} dt \int_0^{\pi} \frac{\rho^2 e^{it(X-s)+lY}}{(1-\psi)^2} \, dl; \ 1 \leq |X-e| < \varepsilon s, 1 \leq |Y| < \varepsilon s \right].
\]

By means of the indefinite integral \( \int_0^{\infty} u^{-1} e^{Yu} \, du, \) we integrate by parts as in \( (7.6) \) to see that the upper limit \( \pi \) of the inner integral may be replaced by \( \alpha/|Y| \) with an arbitrarily small \( \alpha > 0; \) also \( 1/|X-s| \) may be replaced by \( \alpha/|X-s|. \) These in turn allow \( e^{it(X-s)+lY} \) in the integrand to be replaced by \( 1. \) Now observing that

\[
\int_{1/s}^{1/|X-s|} dt \int_0^{1/|X-s|} \frac{\rho^2 dl}{(1-\psi)^2} = \int_{1/s}^{1/|X-s|} g(Yt) \frac{dt}{t} (1 + o(1)),
\]

where \( g(x) = \int_0^{1/|x|} 4\sigma^4[Q(1,u)]^{-2} \, du, \) that \( g(x) \to \pi/\lambda (x \to 0) \) and \( g(x) < C/|x| \ (|x| > 1) \) and then that the double integral above takes on the form \( (\pi/\lambda) \log[s/(|X-s| \vee |Y|)] \cdot (1 + o(1)) \) as \( (|X-s| \vee |Y|)/s \to 0, \) we obtain

\[
J_{222} = \frac{2}{\lambda} E \left[ X^2 \log \frac{s}{|X-s| \vee |Y|}; 1 \leq |X-s| < \varepsilon s, 1 \leq |Y| < \varepsilon s \right] (1 + o(1)) + o(1).
\]

In the same way we also obtain

\[
J_{223} = \frac{2}{\lambda} E \left[ X^2 \log \frac{s}{|X-s|}; 1 \leq |X-s| < \varepsilon s, Y = 0 \right] (1 + o(1)) + o(1);
\]

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Thus we conclude that $J_{222} + J_{223} + J_3 = 2\lambda^{-1} M_\varepsilon(s)(1 + o(1)) + o(1)$. The proof of (7.2) is complete.

The case $n \neq 0$. In the proof of Theorem 1.2 the term $\Theta_I$ and the second half of $\Theta_{II}$ in (6.8) are disposed of without using the extra moment condition; the contribution of $F_{22}$ given in (6.9) cancels out with that involved in $a(n)H_0(s)$ (see (7.1)). The remaining terms among those arising from $F_2 + F_3$ are the first half of $\Theta_{II}$ in (6.8) and the contribution of $F_{21}$, both of which we must examine. As for $F_{21}$, the factor $\rho''(t)$ may be replaced by $\zeta(t)$. From these observations it follows that for $s > \varepsilon|n|$, as $s \to \infty$,

$$H_n(s) = \frac{1}{\pi} \left( \frac{\sigma_2^2 a^*(n)}{s^2/\lambda} - \frac{\lambda^2 |n|^3}{\|s,-n\|^2 s^2} \right) \left[ 1 + o(1) \right] + \frac{J^A + J^B}{2\pi s^2},$$

where

$$J^A = - \int_{1/s < |t| < \pi} [e_n(t) - a(n)]\zeta(t) e^{-ist} dt,$$

$$J^B = -\frac{i}{2\pi} \int_{1/s < |t| < \pi} e^{-ist} dt \int_0^\pi \rho(t) \frac{E[X^2e^{iYt}(e^{iXt} - 1)]}{(1 - \psi)^2} \sin nldl,$$

and $o(1)$ is uniform in $n$. The estimation of $J^A$ and $J^B$ proceeds parallel to that of $J$, and we only point out what modification is needed. To facilitate the exposition we write $\zeta^A$, $J_k^A$, etc. for the corresponding functions.

First we prove that

$$J^B = |n| M_\varepsilon(s) \times o(1).$$

We must show that the convergence is uniform in $n$. Those for which this matters are the convergence in (7.3) with $\zeta^B_2$ in place of $\zeta_2$ and the estimation of $J^B_{222} + J^B_{223} + J^B_3$. The former one, for which the Riemann-Lebesgue lemma is used, can be disposed of by applying Lemma 11.1. For the latter we observe that first $1 - \psi$ may be replaced by $\frac{1}{2}Q$ and then $e^{iYt}$ by $i \sin Yt$; hence it suffices to verify

$$E \left[ X^2 \int_{s/|X-s| < 1} \frac{dt}{|t|^{1/|Y|}} \frac{\rho(t) \sin Yt}{|Q(t,l)|^2} dl; |X - s| < \varepsilon s, 0 < |Y| < \varepsilon s \right] = o(1).$$

This however is obvious from

$$\int_0^1 dt \int_0^\infty (t^2 + l^2)^{-2} tl^2 dl = \frac{1}{2} \arctan \alpha \leq \alpha/2 \ (\alpha > 0).$$

Thus (7.8) has been proved.

Since both $e_n(t)/n$ and $te_n(t)/n$ are uniformly bounded and $e_n(t)/n \to 0$ as $t \to 0$, the very same arguments leading to (7.3) verify that as $s \to \infty$,

$$J^A = 2\lambda^{-1} o(n) M_\varepsilon(s)(1 + o_b(1)),$$

but here uniformity of $o_b(1)$ is not claimed (and not true in general). To get some uniform estimate we use the decomposition $e_n(t) = |n| [f(\lambda nt)/\sigma_n^2 + r_n(t) + h_n^o(t)]$ given in Lemma 5.9. According to the estimates stated therein the contribution of
Finally use the bound $a(n)$ is $o(1)$. We then infer from (7.3) that

$$J^A = \frac{2}{\lambda} \left( a(n) - \frac{|n|}{\sigma_2^2} \right) M_\epsilon(s)(1 + o(1)) + \int_{1/s < |t| < \pi} \frac{|n|(1 - f(\lambda nt))}{\sigma_2^2} \zeta(t)e^{-ist}dt + o(1).$$

(7.9)

On arguing as in the case of $J_{222}$ (we have the additional factor $|n|(1 - f(\lambda nt)) = (1 - e^{-\lambda|nt|})/\lambda|t|$ in the second integral in (7.7)) the last integral may be written in the form

$$\frac{2|n|}{\lambda \sigma_2^2} E \left[ X^2 \log \frac{s}{|X - s| \lor |Y| \lor n} ; 1 \leq |X - s| \lor |Y| < \varepsilon s \right] (1 + o(1)) + o(1).$$

(7.10)

Finally use the bound $a(n) \geq |n|/\sigma_2^2$ (7.31.1) and note that the expectation above is not larger than $M_\epsilon(s)$ to obtain the second assertion of Theorem 1.3. This accomplishes the proof of Theorem 1.3.

8. Proof of Theorem 1.4

Although Theorem 1.4 can be derived from Theorem 1.3 by elementary computations, here is given a direct proof. We are to make an estimation of the integrated tail $E_n(s) = H_n(s) + H_n(s + 1) + \cdots$ in the case $\delta = 0$. For each $\alpha > 0$ define a probability, $c_\alpha$, say, on $\mathbb{Z}$ by

$$c_\alpha(0) = \frac{1}{\pi \alpha} - \frac{2e^{-2\pi \alpha}}{1 - e^{-2\pi \alpha}}, \quad c_\alpha(s) = \frac{1}{\pi} \cdot \frac{\alpha}{\alpha^2 + s^2} \quad (s \neq 0)$$

and put $C_\alpha(s) = c_\alpha(s) + c_\alpha(s + 1) + \cdots$. Using the Poisson summation formula one sees that

$$\hat{c}_\alpha(t) := \sum_s c_\alpha(s)e^{ist} = \sum_s e^{-\alpha|t|} - \frac{2e^{-2\pi \alpha}}{1 - e^{-2\pi \alpha}};$$

hence

$$C_\alpha(s) = \frac{\alpha}{\pi s} + O \left( \frac{\alpha}{(\alpha^2 + s^2)^2} \right) \text{ as } \frac{\alpha}{s} \to 0 \text{ and } \hat{c}_\alpha(t) = e^{-\alpha|t|} + r_\alpha(t)$$

with $r_\alpha(t)$ being differentiable arbitrarily many times, $r_\alpha(0) = r'_\alpha(0) = 0$ and $r''_\alpha(t)$ bounded for $\alpha \geq 1$, $|t| < \pi$. In view of (2.11) and Lemma 5.1, $\hat{H}_n(t) = 1 - a^*(n)\rho(t) + o(nt)$ as $nt \to 0$, in particular $|\hat{H}_n(t) - \hat{c}_\sigma a^*(n)(t)|/t$ is integrable about the origin. Also, as in the proof of Lemma 5.2, one observes that $\hat{H}'_n(t) = O(n)$ and $\hat{H}''_n(t) = O(n/t)$ $(t \neq 0)$. Now we take $\alpha = \sigma^2 a^*(n)$ and compare $E_n$ with $C_\alpha$:

$$E_n(s) - C_{\sigma^2 a^*(n)}(s) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{\hat{H}_n(t) - \hat{c}_\sigma a^*(n)(t)}{1 - e^{-it}} e^{-ist}dt.$$

Splitting the range of integration at $t = \pm K/s$ and performing an integration by parts for the integral over $K/s \leq |t| \leq \pi$, one infers that the integral on the right side may be written as

$$-\frac{1}{s} \int_{K/s < |t| < \pi} \frac{\hat{H}_n(t)}{1 - e^{-it}} e^{-ist}dt - \frac{2\sigma^2 a^*(n)}{s} \int_{K/s}^{\pi} \frac{e^{-\sigma^2 a^*(n)t}}{t} \cos st dt + o \left( \frac{|n| \lor 1}{s} \right)$$

as $s/(|n| \lor 1) \to \infty$ for each $K > 1$. On integrating by parts once more, the first integral is dominated by a constant times $|n|/K$. On the other hand, changing the
variable shows that the second integral is dominated by $1/K$. These together verify that as $s/(|n| \vee 1) \to \infty$, $E_n(s) - \sigma^2 a^*(n)/\pi s = o((|n| \vee 1)/s)$ as desired.

9. The case $\delta \geq 1$

In this section we consider the case when the moment condition \((1.1)\) holds for some $\delta \geq 1$. The main results are given in \((9.5)\) and \((9.7)\), where all the third moments are supposed to vanish.

Make the decomposition $\pi_0(t) = I(t) + II(t)$, where

$$I(t) = \frac{1}{2\pi} \int_{-\pi}^\pi \frac{2dl}{Q(t,l)} \quad \text{and} \quad II(t) = \frac{1}{2\pi} \int_{-\pi}^\pi \left[ \frac{1}{1 - \psi(t,l)} - \frac{2}{Q(t,l)} \right] dl.$$

Then

$$I(t) = \frac{2\lambda}{\pi |t| \sigma^2_1} \left( \frac{\pi}{2} - \arctan \left( \frac{\lambda |t|}{\pi} \right) \right) = \frac{1}{\sigma^2|t|} - \frac{2}{(\sigma_2^2 \pi)^2} + o_2(|t|^2 + \cdots).$$

For evaluation of $II(t)$ we set $f(t,l) = \psi(t,l) - 1 + \frac{1}{2} Q(t,l)$ and further decompose

$$II(t) = \frac{1}{\pi} \int_{-\pi}^\pi \frac{f(0,l)}{(1 - \psi(t,l))Q(t,l)} dl + \frac{1}{\pi} \int_{-\pi}^\pi \frac{f(t,l) - f(0,l)}{(1 - \psi(t,l))Q(t,l)} dl.$$

Suppose $1 \leq \delta < 2$. Then, the first term on the right side can be written as $C^* / \sigma^2_2 + 2/(\sigma_2^2 \pi)^2 + o(|t|^{\delta-1})$, where we have used the identity

$$C^* = \int_{-\pi}^\pi \left[ \frac{\sigma^2_2}{1 - \phi(l)} - \frac{2}{l^2} \right] dl = \frac{1}{2 \pi} \int_{-\pi}^\pi \left[ \frac{2}{l^2} - \frac{1}{\cos l} \right] dl = -\frac{2}{\pi^2}$$

(the first equality is simply by definition of $C^*$ given in Remark 1 (ii)). On the other hand,

$$f(t,l) - f(0,l) = -\frac{i}{6} E[X^3] t^3 - \frac{i}{2} E[X^2 Y t^2 l + X Y^2 t^2 ld] + o(|t|^{2+\delta} + |t| l^{1+\delta}),$$

as $|t| + |l| \to 0$, which together with the formulae $\int_0^\infty [Q(1,u)]^{-2} du = \pi/4(\sigma_1 \sigma)^2$ and $\int_0^\infty u^2 [Q(1,u)]^{-2} du = \pi/(4\sigma_2^2 \pi)^2$ shows that the second term in \((9.2)\) equals

$$-\frac{i}{6}(\sigma_1 \sigma)^{-2} E[X^3] - \frac{i}{2}(\sigma_2 \sigma)^{-2} E[X^2 Y]) \log |l| + o(|l|^{\delta-1})$$

in view of Lemma \(2.3\). It is worth noting that the term led by $E[X^2 Y]$ contributes only a constant multiple of $|t|$ (the next order term of the expansion) since it is an odd function of $l$. In any way, combined with \((9.1)\), these estimates give

$$\sigma^2 \pi_0(t) = |t|^{-1} + \lambda C^* - i((6\sigma^2_2)^{-1} E[X^3] + (2\sigma^2_2)^{-1} E[X Y^2]) \log |t| + o(|t|^{\delta-1}),$$

or, what is the same thing,

$$\rho(t) = \sigma^2 |t| - \sigma^2_1 C^* t^2 + iC^t t |t| + o(|t|^{\delta+1}),$$

where $C^* = (6\lambda)^{-1} E[X^3] + 2|t| E[X Y^2]$. One easily obtains that $\rho''(t) = o(|t|^{\delta-2})$ ($t \neq 0$) and then that

$$H_0(s) = \frac{\sigma^2}{\pi s^2} - \frac{2C^\delta}{s^3} + o \left( \frac{\log |s|}{|s|^{2+\delta}} \right) \quad (|s| \to \infty).$$

(If $\delta > 2$, the error term may be replaced by $O(|s|^{-4})$.)
Now we turn to the integral (2.7). The essential contributions to it of the terms
\(-\sigma_1^2C^*t^2\) and \(iC^*|t|\) in (9.3) are given by
\[
-\frac{\sigma_1^2C^*}{4\pi^2} \int_{[-\pi,\pi]^2} \frac{t^2w(t)}{1-\psi(t,\lambda)} e^{i(-st+nl)} dt dl
\]
(9.4)
\[
= -\frac{C^*}{\pi} \frac{\lambda n^2 - \lambda^{-1}s^2}{\| (s,-n) \|^2} + O\left( \log(|n| \vee |s|) + 1 \right)
\]
and
\[
iC^* \int_{[-\pi,\pi]^2} \frac{t|t|w(t)}{1-\psi(t,\lambda)} e^{i(-st+nl)} dt dl
\]
\[
= \frac{C^*}{\pi(\lambda s^2)} \frac{2|n|s}{\| (s,-n) \|^2} + O\left( \log(|n| \vee |s|) + 1 \right)
\]
(9.5)
(as \(\| (s,-n) \| \to \infty \) for both formulae), respectively. Here we truncate the integrand
by \(w(t)\) since the functions \(t^2\) and \(|t|\) are not periodic.

Suppose that \(|n| > \varepsilon |s|\) and \(\delta \geq 1\). Apart from the leading term, there arises
a rational function of \((\hat{s},\hat{n})\) similar to the ones above plus an error term, which
together may be written in the form \(\{s,n\}^4\| (s,-n) \|^6 + o(n^{-2-\delta})\) if \(\delta \leq 2\), where
\(\{s,n\}^4\) represents a homogeneous polynomial of \((s,n)\) of degree 4 with coefficients
that are linear combinations of the third moments \(E[X^3Y^{3-j}\; (j = 0,1,2,3)\).

If \(\delta \geq 2\), one obtains the next order estimate and, in the case when all the third
moments vanish, the result is given in a rather simple form: as \(|n| \to \infty\),
\[
H_n(s) = \frac{1}{\pi} \frac{|n|}{\| (s,-n) \|^2} - \frac{C^*}{\pi} \frac{\lambda n^2 - \lambda^{-1}s^2}{\| (s,-n) \|^2} + O\left( \frac{1}{n^3} \right) \quad (|n| > \varepsilon |s|).
\]
(9.6)

For the case \(|\hat{s}| > \varepsilon |n|\) we examine the contribution of \(-\sigma_1^2C^*t^2\) to the integral
(2.13). To this end we follow the arguments given in the second half of Section
3 with \(\rho\) replaced by \(-\sigma_1^2C^*t^2\). We consider the integral corresponding to that
involving \(F_1\) and seek an analogue of Lemma 4.1. Similarly to the proof of Lemma
(4.1), we find that
\[
\int_{-\pi}^{\pi} e^{-ist} dt \int_{-\pi}^{\pi} w(t) \frac{\sigma_1^2}{Q(t,\lambda)} \left( e^{inl} - 1 \right) dl
\]
\[
= -C^* \left( \frac{\lambda n^2 - \lambda^{-1}s^2}{\| (s,-n) \|^2} + \frac{\lambda}{\pi s^2} \right) + O(|s|^{-N})
\]
for each \(N > 0\). On the other hand, on arguing with \(\rho + \sigma_1^2C^*t^2\) in place of \(\rho\),
the error term in (2.13) becomes \(o((n \log |s|)/|s|^{3+\delta})\) if \(1 \leq \delta \leq 2\) plus a term
involving the third moments as its coefficient; the latter is of the order of magnitude
\(O(n/|s|^3\).\)

Again suppose that \(\delta > 2\) and that all the third moments vanish. Then for
\(|\hat{s}| > \varepsilon |n|\), as \(|\hat{s}| \to \infty\),
\[
H_n(s) = \frac{1}{\pi} \left( \frac{\sigma_1^2a^*(n)}{s^2/\lambda} - \frac{\lambda^2|n|^3}{\| (s,-n) \|^3 s^2} \right) - C^* \left( \frac{\lambda n^2 - \lambda^{-1}s^2}{\| (s,-n) \|^2} + \frac{\lambda}{s^2} \right) + O\left( \frac{n}{|s|^4} \right).
\]
(If \(\delta = 2\), we need to bring in the logarithmic factor in the numerator in the \(O\) term
as in (9.4).) In view of the expansion \(\sigma_1^2a^*(n) = |n| + C^* - (\text{sign} n)E[Y^3]/3\sigma_2^2 + \text{O}(1/n)\) (cf. Appendix of [14]) the two formulae (9.5) and (9.7) are consistent. The
last \(O\) terms in them seem to represent the correct order (i.e. not replaced by a
smaller order term) in general. (This is the case at least for simple random walk for which \(a(n) = |n|\) and the second order term can be explicit.)

The proof of (9.7) is outlined below. First note that the third order term of the expansion of \(\rho(t)\) takes on the form \(|t|^3 (\text{apart from } \lambda \text{ and } \sigma \text{ the coefficient } \alpha \text{ involves only the two fourth moments } E[X^4] \text{ and } E[X^2Y^2]; E[Y^4] \text{ is absorbed in } C^* \text{ and both } E[X^4Y] \text{ and } E[XY^3]\) contribute only the next order term). 

On the one hand, we compute \(I_3 := \int |t|^3 e_n(t) e^{-ist} dt\) in a similar way to the above and find that \(I_3 = O(n/s^4)\). On the other hand, under the present assumptions on the moments, we have \(\left| \frac{\partial^4 F_3}{\partial t^4} \right| \leq |Q|^{-3/2}\); the contribution to the double integral in (3.9) of its even (w.r.t. \(l\)) part is directly evaluated to be \(O(n/s^2)\) (hence \(O(n/s^4)\) as a whole). For the odd part use the last assertion of Lemma 11.4 to have the same bound. As for the function \(F_2\) the factor \(\rho''\) in it may be understood to be \(o(t^{s-1})\) since the terms up to the order of magnitude \(O(t^3)\) may be considered as being subtracted from \(\rho\). Hence its contribution is negligible and (9.7) is concluded.

10. The case \(d \geq 3\) and reduction to the diagonal case

This section concerns the random walk on \(Z^d\) for \(d \geq 2\). In the first half of it we exhibit some algebraic manipulations which reduce our problem to that in the case when \(Q\) is diagonal and in the second some higher dimensional analogue of what is given in Section 2.

Let \(X\) and \(Y\) be, respectively, \(Z^{d-1}\)-valued and \(Z\)-valued random variables of zero mean and finite variance. Let \(R\) be the covariance matrix of \(X\), \(\gamma = E[XY]\) \((\in \mathbb{R}^{d-1})\) and \(\sigma_\theta^2 = E[Y^2]\), so that the covariance matrix of \(S_1 := (X,Y)\) and its quadratic form are given by

\[
Q = \begin{pmatrix}
R & \gamma \\
\gamma & \sigma_\theta^2
\end{pmatrix},
\]

and \(Q(\theta,l) = R(\theta) + 2(\gamma \cdot \theta)l + \sigma_\theta^2 l^2\) \((\theta \in \mathbb{R}^{d-1}, l \in \mathbb{R})\), respectively. Set

\[
\mu = \frac{\gamma}{\sigma_\theta^2} \quad \text{and} \quad \tilde{X} = X - \mu Y
\]

and let \(\tilde{R}\) be the covariance matrix of the random \((d-1)\)-vector \(X - \mu Y\). Each component of \(\tilde{X}\) is perpendicular to \(Y\); \(\tilde{R}\) is the \((d-1)\)-dimensional symmetric matrix whose quadratic form is given by

\[
\tilde{R}(\theta) = E[(\tilde{X} \cdot \theta)^2] = R(\theta) - \sigma_\theta^2 (\mu \cdot \theta)^2 \quad (\theta \in \mathbb{R}^{d-1}),
\]

so that \(\tilde{R} = R - \sigma_\theta^2 \mu^t \mu\) and

\[
Q(\theta,l) = E[(\tilde{X} \cdot \theta + Y \tilde{l})^2] = \tilde{R}(\theta) + \sigma_\theta^2 \tilde{l}^2, \quad \text{where} \quad \tilde{l} = l + \mu \cdot \theta.
\]

\(\tilde{R}\) is positive definite. Indeed, taking \(l = -\mu \cdot \theta\), we have \(\tilde{R}(\theta) = Q(\theta,l) > 0\) for \(\theta \neq 0\).

Denote by \(\tilde{Q}\) the covariance matrix of \((\tilde{X},Y)\) and let \(A\) be the \(d \times d\) matrix which transforms \((\theta,l)\) into \((\theta, \mu \cdot \theta + l)\), and \(A^{-1}\) its inverse:

\[
\tilde{Q} = \begin{pmatrix}
R & 0 \\
0 & \sigma_\theta^2
\end{pmatrix}, \quad A = \begin{pmatrix} I & 0 \\ \mu & 1 \end{pmatrix}, \quad A^{-1} = \begin{pmatrix} I & -\mu \\ 0 & 1 \end{pmatrix},
\]

where \(I\) stands for the unit matrix. Then

\[
Q(\theta,l) = \tilde{Q}(\theta,\tilde{l}) = \tilde{Q}(A[\theta,l]),
\]
where $A[\theta,l]$ denotes the action of $A$ on the $d$-column vector $[\theta,l]$ consisting of a $(d-1)$-vector $\theta$ and a number $l$; hence $Q = tAQA$, det $Q = \det \tilde{Q}$ and

(10.1) \hspace{1cm} Q^{-1}(x,k) = \tilde{Q}^{-1}(\tilde{x},k), \quad \text{where} \quad \tilde{x} = x - \mu k.

Now we consider a random walk $S_n$ on $\mathbb{Z}^d$ with the law of $S_1$ under $P_0$ equal to that of $(X,Y)$ and the corresponding hitting distribution $H_n(x), (x,0) \in L_d$ of the hyperplane $L_d = \{(x,0) : x \in \mathbb{Z}^{d-1}\}$. Let $\psi(\theta,t) = E[e^{iX_\theta+Y_t}]$ \((\theta, t) \in T_{d-1} \times [-\pi, \pi], T_{d-1} = [-\pi, \pi]^{d-1}\). The functions $\pi_n(\theta)$ of $\theta \in T_d \setminus \{0\}$ are defined in the same way as in the case $d = 2$, and the obvious analogue of the Fourier representation of $H_n(x)$ by it is valid:

$$
\pi_k(\theta) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{e^{ikl}}{1 - \psi(\theta,l)} \; dl, \quad H_n(x) = \frac{1}{(2\pi)^{d-1}} \int_{T_{d-1}} \frac{\pi_{-n}(\theta)}{\pi_0(\theta)} e^{-ix\cdot \theta} d\theta \quad (n \neq 0),
$$

and similarly for $H_0$. It therefore follows that if $\tilde{\psi}(\theta,t) = E[e^{i\tilde{X}_\theta+iY_t}]$ \((= \psi(\theta,l - \mu \cdot \theta)) \) and

$$
\pi_k(\theta) = \frac{1}{2\pi} \int_{\mu \cdot \theta - \pi}^{\mu \cdot \theta + \pi} \frac{e^{-ikl}}{1 - \psi(\theta,l)} \; dl = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{e^{-ikl}}{1 - \psi(\theta,l)} \; dl \quad (\theta \neq 0),
$$

(note that $\tilde{\psi}(\theta, \cdot)$ is periodic), then $\pi_k(\theta) = \tilde{\pi}_k(\theta)e^{ik\mu \cdot \theta}$ so that

(10.2) \hspace{1cm} H_n(x) = \frac{1}{(2\pi)^{d-1}} \int_{T_{d-1}} \frac{\tilde{\pi}_{-n}(\theta)}{\tilde{\pi}_0(\theta)} e^{-i(x+n\mu)\cdot \theta} d\theta \quad (n \neq 0).

By virtue of the last formula we may suppose that $Q(\theta,l)$ is of the form $R(\theta) + \sigma^2_d l^2$ for evaluation of $H_n(x)$, in particular for the proofs of Theorems 1.1 and 1.2 (see below for more details).

Let $d \geq 3$. The principal term of $H_n$ in the higher dimensions is derived by using the classical formula

$$
\frac{1}{(2\pi)^d} \int_{\mathbb{R}^d} \frac{|\theta|^2}{|\theta|^2 + l^2} e^{-ix\cdot \theta} e^{in\theta} \; d\theta = \frac{\pi}{(2\pi)^{d-1}} \int_{\mathbb{R}^{d-1}} e^{-|n||\theta|} e^{-ix\cdot \theta} \; d\theta = \frac{\Gamma(d/2)}{2\pi^{d/2}} \frac{|n|}{(n^2 + |x|^2)^{d/2}} \quad (\text{[8], p.6}).
$$

Write $\tilde{l} = \mu \cdot \theta + l$ so that $Q(\theta,l) = \tilde{Q}(\theta,\tilde{l}) = \tilde{R}(\theta) + \sigma^2_d \tilde{\theta}^2$. Then

$$
\pi_0(\theta) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{dl}{1 - \psi} = \frac{1}{2\pi} \int_{-\mu \cdot \theta - \pi}^{-\mu \cdot \theta + \pi} \frac{dl}{1 - \psi(\theta,l)} \sim \frac{1}{\pi} \int_{-\mu \cdot \theta - \pi}^{-\mu \cdot \theta + \pi} \frac{dl}{Q(\theta,l)} = \frac{1}{\sigma_d \sqrt{\tilde{R}(\theta)}} + O(1).
$$

Consequently

$$
\rho(\theta) = \sigma_d \sqrt{\tilde{R}(\theta)} + o(|\theta|).
$$

By simple changes of variables we derive from this and (10.2) that for $x \in \mathbb{R}^{d-1}$,

$$
H_n(x) \sim \frac{\sigma_d}{(2\pi)^d} \int_{T_{d-1}} \sqrt{\tilde{R}(\theta)} e^{-i(x+n\mu)\cdot \theta} \; d\theta \int_{-\pi}^{\pi} \frac{2e^{in\theta} dl}{\tilde{R}(\theta) + \sigma^2_d l^2} \sim \frac{1}{(2\pi)^d \det R^{-1/2}} \int_{\mathbb{R}^{d-1}} |\theta| e^{-i \sqrt{\tilde{R}^{-1}(x+n\mu)\cdot \theta}} \; d\theta \int_{-\infty}^{\infty} \frac{2e^{in\theta} \sigma_d \; dl}{|\theta|^2 + l^2}.
$$
Hence by (10.3) and (10.1) (note that \( \tilde{Q}^{-1}(x + n\mu, -n) = Q^{-1}(x, -n) \)),

\[
H_n(x) \sim \frac{\Gamma(d/2)}{\pi^{d/2} \sqrt{\det Q}} \cdot \frac{|n|}{[(n/\sigma_d)^2 + R^{-1}(x + n\mu)]^{d/2}}
\]

\[
= \frac{\Gamma(d/2)}{\pi^{d/2}} \cdot \frac{|n|}{\|x - (x, -n)\|^{d}}.
\]

This gives a correct asymptotic form of \( H_n(x) \) as \(|n| \to \infty\). If \(|n|\) remains finite, \(|n|\) in the numerator must be replaced by \( \sigma^2_d(n) \) as in the two-dimensional case. Thus

**Theorem 10.1.** If the random walk \( S_n \) on \( \mathbb{Z}^d \) (\( d \geq 3 \)) is irreducible and has zero mean and finite variances, then

\[
H_n(x) = \frac{\Gamma(d/2)}{\pi^{d/2}} \cdot \frac{\sigma^2_d(n)}{\|x - (x, -n)\|^{d}} (1 + o(1)).
\]

For verification, in the case \( n \geq |x| \), the proof given in Section 3 straightforwardly applies to the higher-dimensional case. In the case \( n < |x| \) the arguments made for the two dimensions are only simplified. The analogues of the two lemmas of Section 4 are verified by essentially the same proofs; the lemmas of Section 5 are almost obviously extended to the dimensions \( d \geq 3 \). It is noted that if \( \nabla \) denotes the gradient operator with respect to \( \theta \in \mathbb{R}^{d-1} \) and \( \omega = x/|x| \), then as \( \theta \to 0 \),

\[
(\omega \cdot \nabla)\rho(\theta) = \sigma_d \frac{\omega \cdot \bar{R} \theta}{|\bar{R}(\theta)|^{1/2}} + o(1)
\]

and

\[
(\omega \cdot \nabla)^2 \rho(\theta) = \sigma_d \frac{\bar{R}(\omega) - (\omega \cdot \bar{R} \theta)^2 / \bar{R}(\theta)}{|\bar{R}(\theta)|^{1/2}} + o\left(\frac{1}{|\theta|}\right);
\]

in particular \( (\omega \cdot \nabla)^2 \rho(\theta) \) is integrable on \(|\theta| < 1\), which trivializes the argument given for the estimate of \( H_0 \) in section 6 and makes the moment condition \( E[|X|^2 \log^+ |X|] < \infty \) dispensable.

### 11. Appendix

**(A)** We give a proof of (2.2) and (2.3), namely \( \hat{H}_n(t) = \pi_n(0, t)/\pi_0(t) \) (\( n \neq 0 \)) and \( \hat{H}_0(t) = 1 - 1/\pi_0(t) \), respectively. Let \( p^v(x, y) = P_x[S_n = y] \) and define for \(|z| < 1\),

\[
\pi_k(t, z) = \sum_{\nu=0}^{\infty} \sum_{s \in \mathbb{Z}} p^{\nu}((0, 0), (s, k)) e^{its} z^\nu.
\]

Then \( \sum_k \pi_k(t, z) e^{ikl} = (1 - z\psi(t, l))^{-1} \) and hence for \( t \neq 0 \),

\[
\pi_k(t, r) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{e^{-ikl} dl}{1 - r\psi(t, l)} \longrightarrow \pi_k(t) \quad \text{as} \quad r \uparrow 1.
\]

It is convenient to bring in the joint distribution

\[
f_n(\tau, s) = P_{(0, n)}[\tau(L) = \tau, S_{\tau}(L) = (s, 0)]
\]

and its Abel-Fourier series

\[
\Phi_n(t, z) = \sum_{\tau=1}^{\infty} \sum_{s \in \mathbb{Z}} f_n(\tau, s) e^{its} z^\tau.
\]
Using \( p^\nu((0, n), (s, 0)) = \sum_{\nu=1}^\infty \sum_{s \in \mathbb{Z}} f_n(\tau, j)p^{\nu-\tau}((j, 0), (s, 0)) \) \((\nu \geq 1)\) and making a routine computation, one then finds that for \( t \in \mathbb{R} \) and \(|z| < 1\),

\[
\pi_{-n}(t, z) = \sum_{\nu=1}^\infty \sum_{s \in \mathbb{Z}} p^\nu((0, n), (s, 0)) e^{ists} z^\nu
\]

or, what is the same thing,

\[
(11.1) \quad \Phi_n(t, z) = \frac{\pi_{-n}(t, z)}{\pi_0(t, z)} \quad (n \neq 0), \quad \Phi_0(t, z) = 1 - \frac{1}{\pi_0(t, z)},
\]

which, on setting \( z = 1 \) (for \( 0 < |t| \leq \pi \)), reduces to (2.2) and (2.3), respectively.

(B) Here we collect several lemmas concerning Fourier analysis that are used in this paper.

**Lemma 11.1.** Let \( f_n(t, l) \) be a sequence of measurable functions on \((-\pi, \pi]^2\) of the form

\[
(11.2) \quad f_n(t, l) = a(t, l) \frac{1 - \cos nl}{nl^2} \quad \text{or} \quad f_n(t, l) = b(t, l) \frac{\sin nl}{nl},
\]

\((n = 1, 2, \ldots)\). Suppose that \( \int_{-\pi}^{\pi} |a(t, l)| dt \) is bounded and tends to zero as \( l \to 0 \) in the first case and \( b(t, l) \) is integrable on \([-\pi, \pi]^2\) in the second case. Then

\[
(11.3) \quad \int_{-\pi}^{\pi} e^{ist} dt \int_{-\pi}^{\pi} f_n(t, l) dl \to 0 \quad \text{as} \quad |s| \to \infty \quad \text{uniformly in} \quad n.
\]

**Proof.** Put \( g_{n, \varepsilon}(t) = \int_{|s| < |t| < \varepsilon} f_n(t, l) dl \) and \( h_{n, \varepsilon}(t) = \int_{|s| < \varepsilon} f_n(t, l) dl \). Then from the assumptions on \( f_n \) of the lemma it follows that

\[
\lim_{n \to \infty} \int_{-\pi}^{\pi} |g_{n, \varepsilon}(t)| dt = 0 \quad \text{for each} \quad \varepsilon > 0, \quad \text{and} \quad \sup_n \int_{-\pi}^{\pi} |h_{n, \varepsilon}(t)| dt \to 0 \quad \text{as} \quad \varepsilon \downarrow 0,
\]

which together show that \( \lim_{n \to \infty} \int_{-\pi}^{\pi} \left| \int_{-\pi}^{\pi} f_n(t, l) dl \right| dt = 0 \), reducing the assertion to be proved to the Riemann-Lebesgue lemma.

**Remark** (Remark to Lemma 11.1). (i) The pair of two function forms in (11.2) may appear ill-matched, but actually they are well on balance if the supposed conditions on \( a(t, l) \) and \( b(t, l) \) in the lemma are taken into account. Indeed, on the one hand, the function \((1 - \cos nl)/nl^2\) (Fejér’s kernel) approaches \( \pi \) times Dirac’s delta function as \( n \to \infty \); on the other hand, \( \sin nl/\pi \) times Dirichlet’s kernel and the factor \( 1/\pi \) is apparently superfluous in comparison to the former one, which however is needed for counterweighing the possible singularity of \( \int b(t, l) dt \) at \( l = 0 \) that duly arises: in our application of Lemma 10.1 these two function forms come up in pairs (see the definitions of \( \Theta_I \) and \( \Theta_{II} \) in Section 6), where we encounter the situation such that a priori we know only \( \int |b(t, l)| dt = o(1/l) \).

(ii) If only boundedness of \( \int_{-\pi}^{\pi} |a(t, l)| dt \) is assumed, the convergence in (11.3) still holds boundedly but it is not necessarily uniform. E.g., if \( a(t, l) = |l|/(t^2 + l^2) \), then \( \int_{-\pi}^{\pi} |a(t, l)| dt \) is bounded, whereas the double integral in (11.3), taking on the form

\[
\frac{4}{n} \int_0^{\pi} \cos st \int_0^{\pi} \frac{1 - \cos nl}{(t^2 + l^2)} dl = 2\pi \int_0^{\pi} e^{-|s/n|u} \frac{1 - \cos u}{u^2} du + O\left(\frac{1}{s}\right),
\]

does not uniformly approach zero as \( s \to \infty \).
Lemma 11.2. Let \( f_n(t) \) be a sequence of continuous functions on the (half-open) interval \((0, 1]\) such that as \( t \to 0 \),
\[
\sup_n |f_n(t)| = o(t^{-1}),
\]
and such that the \( f_n \) are continuously differentiable in \( t > 0 \) and satisfy
\[
\sup_n |f'_n(t)| = O(t^{-2})
\]
or more generally \( \sup_n \int_0^1 |df_n(u)| = O(1/t) \) (\( t \to 0 \)). Then for each \( \alpha > 0 \),
\[
\int_0^1 f_n(t) \sin st \, dt \to 0 \quad \text{and} \quad \int_{\alpha/s}^1 f_n(t) \cos st \, dt \to 0
\]
as \( s \to \infty \) uniformly in \( n \).

If, in addition, the improper integrals \( \int_{s+0}^1 f_n(t) \, dt \) exist and approach zero as \( \varepsilon \downarrow 0 \) uniformly in \( n \), then
\[
\int_{s+0}^1 f_n(t) \cos st \, dt \to 0 \quad \text{as} \quad s \to \infty \quad \text{uniformly in} \quad n.
\]
Moreover, if \( 0 < \delta < 1 \) and the right sides in (11.4) and (11.5) are replaced by \( o(t^{1-\delta}) \) and \( O(t^{1-\delta}) \), respectively, then \( \int_0^1 f_n(t)e^{ist} \, dt = o(|s|^{-\delta}) \) as \( |s| \to \infty \) uniformly in \( n \).

Proof. From (11.4) it follows that \( \sup_n \int_{\alpha/s}^{M/s} |f_n(t)| \, dt = o(1) \) for each \( M > \alpha \) and
\[
\sup_n \int_0^{\alpha/s} |f_n(t)| \, dt = o(1/s) \quad \text{for each} \quad \alpha > 0.
\]
On the other hand, integrating by parts yields that as \( s \to \infty \) and \( M \to \infty \) in this order,
\[
\int_{M/s}^1 f_n(t)e^{ist} \, dt = \frac{1}{is}[f_n(t)e^{ist}]_{t=M/s} - \frac{1}{is} \int_{M/s}^1 e^{ist} df_n(t) = O(1/M) \to 0.
\]
Combining these yields the relation (11.6). The last assertion is verified in the same way.

For the second assertion of the lemma, using the supposition of it, we observe that \( \int_{s+0}^{\alpha/s} f_n(t) \cos st \, dt = \int_0^{\alpha/s} f_n(t)(\cos st - 1) \, dt + o(1) \), but the first term is also \( o(1) \) owing to (11.7).

\[
\Box
\]

Lemma 11.3. Let \( \Lambda \) be any parameter set and \( \{f_\lambda(t)\} \) a family of functions on \((0, \infty)\) with parameter \( \lambda \in \Lambda \) such that
\[
\sup_\lambda |f_\lambda(1)| < \infty \quad \text{and} \quad \sup_\lambda \int_0^\varepsilon |f_\lambda(t)| \, dt \to 0 \quad \text{as} \quad \varepsilon \to 0
\]
and such that for each \( \varepsilon > 0 \), \( \sup_\lambda \int_{\varepsilon}^\infty |df_\lambda(t)| < \infty \) (namely the total variations of \( f_\lambda \) on \([\varepsilon, \infty)\) are bounded). Then
\[
\int_0^M f_\lambda(t)e^{ist} \, dt \to 0 \quad \text{as} \quad |s| \to \infty \quad \text{uniformly in} \quad \lambda \in \Lambda \quad \text{and} \quad M > 1.
\]

Proof. Integrating by parts we obtain \( \limsup_{s \to \infty} \sup_{\lambda, M} \left| \int_{\varepsilon}^M f_\lambda(t)e^{ist} \, dt \right| = 0 \) for each \( \varepsilon > 0 \). The assertion of the lemma then follows from the second condition in (11.8). \( \Box \)
Lemma 11.4. Let $\omega$ be a unit vector in $\mathbb{R}^d$ and $f(\theta)$ a continuous function on $0 < |\theta| < 2$, $\theta \in \mathbb{R}^d$ such that for some constants $0 < \delta < 1$, $K$ and $M_\omega$,
\begin{equation}
|f(\theta)| \leq K|\theta|^{d-\delta} \quad (|\theta| < 2),
\end{equation}

\begin{equation}
|f(\theta) - f(\theta + u\omega)| \leq M_\omega|u|^\delta|\theta|^{-\delta-d} \quad \text{if} \quad 0 < u < \theta \cdot \omega \quad \text{or} \quad 0 > u > \theta \cdot \omega.
\end{equation}

Then
\begin{equation}
\left| \int_{|\theta| \leq 1} f(\theta)e^{-ir\omega \cdot \theta} d\theta \right| \leq C_\omega r^{-\delta} \log r \quad (r > 2\pi),
\end{equation}

where the constant $C_\omega$ may be taken as $A\lambda_d(K + M_\omega)((1-\delta)\delta)^{-\delta}$ with a universal constant $A$ and a constant $\lambda_d$ depending only on $d$. If $f$ satisfies the first condition (11.9) and is differentiable for $\theta \neq 0$ with $|\omega \cdot \nabla f(\theta)| = O(|\theta|^{d-\delta-1})$, then the right side of (11.10) may be replaced by $C' r^{-\delta}$.

Moreover if $|f(\theta)| \leq K/|\theta|^d$ (i.e., (11.9) with $\delta = 0$) and
\begin{equation}
|f(\theta) - f(\theta + u\omega)| \leq M_\omega|\theta|^{-\delta-d}|\log u|^{-1} \quad \text{for} \quad 0 < u < \theta \cdot \omega \leq 1/2,
\end{equation}

then for $\alpha > 0$,
\begin{equation}
\left| \int_{\omega \cdot \theta \geq \alpha/r, |\theta| \leq 1} f(\theta)e^{-ir\omega \cdot \theta} d\theta \right| \leq A_\alpha \lambda_d(K + M_\omega).
\end{equation}

Proof. Use the argument given in the beginning of §3, Chapter II of [16]. The details are omitted since the proof is the same as for Lemma 24 of [10].

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