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Form factor expansion of the row and diagonal correlation functions of the two-dimensional Ising model

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Abstract

We derive and prove exponential and form factor expansions of the row correlation function $\langle \sigma_{0,0} \sigma_{0,N} \rangle$ and the diagonal correlation function $\langle \sigma_{0,0} \sigma_{N,N} \rangle$ of the two-dimensional Ising model.

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1. Introduction

The correlation functions $\langle \sigma_{0,0} \sigma_{M,N} \rangle$ of the two-dimensional Ising model with horizontal (vertical) interaction energies E_1 (E_2) can be written in many different ways which appear to be different but which in fact are equal. They were first expressed as determinants by Kaufman and Onsager [1]. Later Montroll, Potts and Ward [2] demonstrated that if an arbitrary path is drawn on the lattice connecting the point $(0, 0)$ with the point (M, N) then the correlation can be expressed as a determinant whose size in general is twice the length of the path. The correlations $\langle \sigma_{0,0} \sigma_{0,N} \rangle$ and $\langle \sigma_{0,0} \sigma_{N,N} \rangle$ can both be expressed as $N \times N$ Toeplitz determinants [1–3], and expressions of $\langle \sigma_{0,0} \sigma_{M,N} \rangle$ as determinants of size M and $M + 1$ for $M \geq N$ were given by Yamada [4, 5]. Furthermore, the correlations $\langle \sigma_{0,0} \sigma_{M,N} \rangle$ for all finite M, N were expressed as determinants of Fredholm operators by Cheng and Wu [6].

The representations of the correlations as finite size determinants gives an efficient evaluation when the separation is small but to investigate the large separation behaviour alternative representations are needed. The first such result is the limiting behaviour for $T < T_c$

$$\begin{aligned} S_\infty &= \lim_{N \rightarrow \infty} \langle \sigma_{00} \sigma_{0N} \rangle = \lim_{N \rightarrow \infty} \langle \sigma_{00} \sigma_{NN} \rangle \\ &= \{1 - (\sinh 2E_1/kT \sinh 2E_2/kT)^{-2}\}^{1/4}, \end{aligned} \quad (1)$$

which is most easily computed [2] by the use of Szegő's theorem [7, 8].

The first large separation expansion for both $T < T_c$ and $T > T_c$ beyond the limiting value (1) was given in 1966 by Wu [9] for $\langle \sigma_{00} \sigma_{0N} \rangle$ by applying a Wiener–Hopf procedure to the $N \times N$ Toeplitz determinant representation. Shortly thereafter Cheng and Wu [6] obtained the leading term of the large separation behaviour of $\langle \sigma_{00} \sigma_{MN} \rangle$ by applying a Wiener–Hopf procedure to the Fredholm determinant representation. This derivation is formally valid only for $M \neq 0$, and even though it is expected that the result of [6] with M formally set equal to zero should agree with the result of [9], there is no analytic derivation in the literature that for $T < T_c$ the two results are in fact equal (even though the equality has been verified to large orders in the low temperature expansion.)

The expansions of [9] and [6] may be considered as the first terms in a systematic expansion of the correlations. The expansion technique of [6] which starts from the Fredholm determinant representation was carried out to all orders by Wu, McCoy, Tracy and Barouch [10] in 1976. It was found that the correlations can be written in the following exponential form,

$$\langle \sigma_{00} \sigma_{MN} \rangle_{T < T_c} = S_\infty \exp \sum_{n=1}^{\infty} F_{MN}^{(2n)} \quad \text{for } T < T_c, \quad (2)$$

and as

$$\langle \sigma_{00} \sigma_{MN} \rangle_{T > T_c} = \widehat{S}_\infty \sum_{m=0}^{\infty} G_{MN}^{(2m+1)} \exp \sum_{n=1}^{\infty} \widehat{F}_{MN}^{(2n)} \quad \text{for } T > T_c, \quad (3)$$

where

$$\widehat{S}_\infty = \{1 - (\sinh 2E_1/kT \sinh 2E_2/kT)^2\}^{1/4}. \quad (4)$$

In [10] the expressions for $F_{MN}^{(j)}$, $\widehat{F}_{MN}^{(j)}$ and $G_{MN}^{(j)}$ are given as $2j$ -fold multiple-dimensional integrals.

The exponentials in (2) and (3) may be expanded to give what is called a form factor expansion

$$\langle \sigma_{00} \sigma_{MN} \rangle_{T < T_c} = S_\infty \sum_{n=0}^{\infty} f_{MN}^{(2n)} \quad \text{for } T < T_c \quad (5)$$

and

$$\langle \sigma_{00} \sigma_{MN} \rangle_{T > T_c} = \widehat{S}_\infty \sum_{n=0}^{\infty} f_{MN}^{(2n+1)} \quad \text{for } T > T_c. \quad (6)$$

The first few terms in this expansion were given in [10]. In the scaling limit $N \rightarrow \infty$, $T \rightarrow T_c$ with $N|T - T_c|$ fixed the full expansion was given by Nappi [11]. For fixed N and $T < T_c$ the full expansion (5) was given by Palmer and Tracy [12]. Both of the cases $T < T_c$ and $T > T_c$ were treated by Nickel [13, 14]. An independent expansion was given by Yamada [15], and this is shown in [14] to agree with the results from the expansion of the exponential forms of [10].

The results for the exponential representation of the correlations [10] were obtained by extending to all orders the iterative expansion of the Fredholm determinant representation [6]. However, as noted above, the result of [6] for $F_{M,N}^{(2)}$ when specialized to $M = 0$ ‘looks different’ from the corresponding result for $\langle \sigma_{0,0} \sigma_{0,N} \rangle$ obtained in [9]. Moreover, the leading order large N behaviour of $\langle \sigma_{0,0} \sigma_{N,N} \rangle$ is obtained [16] from the results for of [9] for $\langle \sigma_{0,0} \sigma_{0,N} \rangle$ and this result looks very different from the result of [10]. Therefore it must be the case that if the Wiener–Hopf procedure of Wu [9], which starts from the $N \times N$ Toeplitz determinant representation of $\langle \sigma_{0,0} \sigma_{0,N} \rangle$ and $\langle \sigma_{0,0} \sigma_{N,N} \rangle$, is iterated to all orders we will obtain

a representation of $\langle \sigma_{0,0} \sigma_{0,N} \rangle$ and $\langle \sigma_{0,0} \sigma_{N,N} \rangle$ which is different from that of [10]. The purpose of this paper is to derive these exponential expansions for both $T < T_c$ and $T > T_c$ and the form factor expansions which follow from them. The results for the case of the diagonal correlation have been previously presented by one of us (BM) in [17] with Boukraa, Hassani, Maillard, Orrick and Zenine. This paper is the proof, derivation and generalization of those results.

In section 2 we summarize the results of our calculations. In section 3 we calculate the exponential representation of the correlation functions $\langle \sigma_{00} \sigma_{0N} \rangle$ and $\langle \sigma_{00} \sigma_{NN} \rangle$ for $T < T_c$. In section 4 we calculate the exponential representations for $T > T_c$. In section 5 we calculate the form factor expansions of $\langle \sigma_{00} \sigma_{0N} \rangle$ and $\langle \sigma_{00} \sigma_{NN} \rangle$ for $T < T_c$ and section 6 we calculate the form factor expansions for $T > T_c$. We conclude in section 7 with a brief discussion of our results.

2. Summary of results

We let D_N stand for $S_N = \langle \sigma_{00} \sigma_{0N} \rangle$ or $C_N = \langle \sigma_{00} \sigma_{NN} \rangle$. Then

$$D_N = \begin{cases} D_N^{(-)} & \text{for } T < T_c \\ D_N^{(+)} & \text{for } T > T_c. \end{cases} \tag{7}$$

The representation of these correlations as an $N \times N$ Toeplitz determinant is [16]

$$D_N = \det \mathbf{A}_N \tag{8}$$

where

$$\mathbf{A}_N = \begin{pmatrix} a_0 & a_{-1} & \dots & a_{1-N} \\ a_1 & a_0 & \dots & a_{2-N} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N-1} & a_{N-2} & \dots & a_0 \end{pmatrix} \tag{9}$$

and

$$a_n = \frac{1}{2\pi i} \oint_{|z|=1} \varphi(z) z^{-n-1} dz, \tag{10}$$

where the path of integration is counterclockwise. The function $\varphi(z)$ is

$$\varphi(z) = \left(\frac{(1 - \alpha_1 z)(1 - \alpha_2 z^{-1})}{(1 - \alpha_1 z^{-1})(1 - \alpha_2 z)} \right)^{1/2}. \tag{11}$$

For the diagonal correlation function C_N

$$\alpha_1 = 0 \quad \text{and} \quad \alpha_2 = (\sinh 2K_1 \sinh 2K_2)^{-1} \tag{12}$$

where $K_j = E_j/kT$. For the row correlation function S_N

$$\alpha_1 = e^{-2K_2} \tanh K_1 \quad \text{and} \quad \alpha_2 = e^{-2K_2} \coth K_1. \tag{13}$$

When $T < T_c$, then $\alpha_1 < \alpha_2 < 1$. In this case we write φ in a factored form as

$$\varphi(z) = P(z)^{-1} Q(z^{-1})^{-1} \tag{14}$$

where

$$P(z) = ((1 - \alpha_2 z)/(1 - \alpha_1 z))^{1/2} \tag{15}$$

and

$$Q(z) = ((1 - \alpha_1 z)/(1 - \alpha_2 z))^{1/2} = 1/P(z). \tag{16}$$

We will prove in section 3 that the correlation function $D_N^{(-)}$ has an exponential expansion

$$D_N^{(-)} = S_\infty \exp \sum_{n=1}^\infty F_N^{(2n)} \tag{17}$$

where

$$S_\infty = \left[\frac{(1 - \alpha_1^2)(1 - \alpha_2^2)}{(1 - \alpha_1 \alpha_2)^2} \right]^{1/4} \tag{18}$$

which for both the diagonal (12) and row (13) specializes to (1), and

$$F_N^{(2n)} = \frac{(-1)^{n+1}}{n(2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i \prod_{j=1}^{2n} \frac{z_j^N}{1 - z_j z_{j+1}} \prod_{k=1}^n P(z_{2k}) P(z_{2k}^{-1}) Q(z_{2k-1}) Q(z_{2k-1}^{-1}) \tag{19}$$

and $z_{2n+1} = z_1$. This agrees with the result given in [17] for the diagonal correlation function $C_N^{(-)}$.

In section 5 we prove that $D_N^{(-)}$ has the form factor expansion

$$D_N^{(-)} = S_\infty \sum_{n=0}^\infty f_N^{(2n)} \tag{20}$$

where $f_N^{(0)} = 1$ and

$$f_N^{(2n)} = \frac{1}{(n!)^2 (2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i z_i^N \prod_{k=1}^n P(z_{2k}) P(z_{2k}^{-1}) Q(z_{2k-1}) Q(z_{2k-1}^{-1}) \\ \times \prod_{l=1}^n \prod_{m=1}^n (1 - z_{2l-1} z_{2m})^{-2} \prod_{1 \leq p < q \leq n} (z_{2p-1} - z_{2q-1})^2 (z_{2p} - z_{2q})^2. \tag{21}$$

This agrees with the result given in [17] for the diagonal correlation function $C_N^{(-)}$.

For $T > T_c$, we consider a new function $\widehat{\varphi}(z)$ such that

$$\widehat{\varphi}(z) = \varphi(z) z = \left(\frac{(1 - \alpha_1 z)(1 - \alpha_2^{-1} z)}{(1 - \alpha_1 z^{-1})(1 - \alpha_2^{-1} z^{-1})} \right)^{1/2} \tag{22}$$

which we write in factored form as

$$\widehat{\varphi}(z) = \widehat{P}(z)^{-1} \widehat{Q}(z^{-1})^{-1} \tag{23}$$

with

$$\widehat{P}(z) = ((1 - \alpha_1 z)(1 - \alpha_2^{-1} z))^{-1/2} \tag{24}$$

and

$$\widehat{Q}(z) = ((1 - \alpha_1 z)(1 - \alpha_2^{-1} z))^{1/2} = 1/\widehat{P}(z). \tag{25}$$

$\widehat{P}(z)$ and $\widehat{Q}(z)$ are analytic and non-zero for $|z| < 1$.

We prove in section 4 that the correlation function $D_N^{(+)}$ has an exponential expansion

$$D_N^{(+)} = -\widehat{S}_\infty \sum_{m=0}^\infty G_N^{(2m+1)} \exp \sum_{n=1}^\infty \widehat{F}_{N+1}^{(2n)} \tag{26}$$

where

$$\widehat{S}_\infty = [(1 - \alpha_1^2)(1 - \alpha_2^{-2})(1 - \alpha_1 \alpha_2^{-1})^2]^{1/4} \tag{27}$$

which for both the diagonal (12) and row (13) correlations specializes to (4) and where $\widehat{F}_N^{(2n)}$ is defined as in (19), but with P and Q replaced by \widehat{P} and \widehat{Q} . Thus we find from (19) that $\widehat{F}_N^{(2n)}$ is

$$\widehat{F}_N^{(2n)} = \frac{(-1)^{n+1}}{n(2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i \prod_{j=1}^{2n} \frac{z_j^N}{1 - z_j z_{j+1}} \prod_{k=1}^n \widehat{P}(z_{2k}) \widehat{P}(z_{2k}^{-1}) \widehat{Q}(z_{2k-1}) \widehat{Q}(z_{2k-1}^{-1}) \tag{28}$$

and that $G_N^{(2n+1)}$ is given by

$$G_N^{(2n+1)} = \frac{1}{(2\pi i)^{2n+1}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n+1} \oint_{|z_i|=1-\epsilon} dz_i z_i^{N+1} \frac{1}{z_1 z_{2n+1}} \prod_{k=1}^{2n} \frac{1}{1 - z_k z_{k+1}} \times \prod_{l=1}^{n+1} \widehat{P}(z_{2l-1}) \widehat{P}(z_{2l-1}^{-1}) \prod_{m=1}^n \widehat{Q}(z_{2m}) \widehat{Q}(z_{2m}^{-1}). \tag{29}$$

Equations (28) and (29) agree with the results given in [17]. Note that for the diagonal correlation function $C_N^{(+)} = \langle \sigma_{00} \sigma_{NN} \rangle$ (12) implies that

$$\widehat{F}_N^{(2n)} = F_N^{(2n)}. \tag{30}$$

In section 6 we prove that $D_N^{(+)}$ has the form factor expansion

$$D_N^{(+)} = -\widehat{S}_\infty \sum_{n=0}^\infty f_N^{(2n+1)} \tag{31}$$

where

$$f_N^{(2n+1)} = -\frac{i}{n!(n+1)!(2\pi)^{2n+1}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n+1} \oint_{|z_i|=1-\epsilon} dz_i z_i^N \prod_{l=1}^{n+1} \widehat{P}(z_{2l-1}) \widehat{P}(z_{2l-1}^{-1}) z_{2l-1}^{-1} \times \prod_{m=1}^n \widehat{Q}(z_{2m}) \widehat{Q}(z_{2m}^{-1}) z_{2m} \prod_{p=1}^{n+1} \prod_{q=1}^n \frac{1}{(1 - z_{2p-1} z_{2q})^2} \prod_{1 \leq j < k \leq n+1} (z_{2j-1} - z_{2k-1})^2 \times \prod_{1 \leq r < s \leq n} (z_{2r} - z_{2s})^2. \tag{32}$$

Equation (32) agrees with result given in [17] for the diagonal correlation function $C_N^{(+)}$.

The proofs of these results are not restricted to the Ising case where the generating function is given by (11) but with a suitable replacement for the factors S_∞ and \widehat{S}_∞ are valid in more general cases, for example the XY model in a magnetic field [18–20]. The results (17)–(21) for $T < T_c$ are valid for any generating function $\varphi(z)$ where $\log \varphi(z)$ is analytic and periodic on $|z| = 1$ and $P(z) = 1/Q(z)$. The results (26)–(32) for $T > T_c$ are similarly valid for any generating function for which $\log z\varphi(z)$ is analytic and periodic on the unit circle $|z| = 1$ and $\widehat{P}(z) = 1/\widehat{Q}(z)$.

3. The exponential expansion for $T < T_c$

In this section, we will use the theory of Wiener–Hopf sum equations to prove that the functions $F_N^{(2n)}$ which appear in equation (17) are given by (19).

When $T < T_c$, then $\alpha_1 < \alpha_2 < 1$ and therefore $P(z)$ and $Q(z)$ are analytic and non-zero for $|z| < 1$. Furthermore, the index of φ is

$$\text{Ind } \varphi = \log \varphi(e^{2\pi i}) - \log \varphi(1) = 0. \tag{33}$$

It follows from (33) that we may use Szegő’s theorem to find

$$\lim_{N \rightarrow \infty} D_N^{(-)} = S_\infty \tag{34}$$

with S_∞ given (18) which reduces to (1) for both the diagonal and the row correlation functions. Therefore we may write

$$D_N^{(-)} = S_\infty \prod_{n=N}^{\infty} D_n^{(-)} / D_{n+1}^{(-)}. \tag{35}$$

3.1. Computation of the ratio $D_N^{(-)} / D_{N+1}^{(-)}$

The ratio $D_N^{(-)} / D_{N+1}^{(-)}$ is given by

$$D_N^{(-)} / D_{N+1}^{(-)} = x_0^{(N)} \tag{36}$$

where $\mathbf{x}^{(N)} = (x_0, x_1, \dots, x_N)$ satisfies

$$\mathbf{A}_{N+1} \mathbf{x}^{(N)} = \mathbf{d}^{(N)} \tag{37}$$

and $d_i^{(N)} = \delta_{i0}$. We indicate that the vector $\mathbf{x}^{(N)}$ has $N + 1$ entries by writing $x_0^{(N)}$.

We will calculate $x_0^{(N)}$ by iterating the procedure given by Wu in section 3 of [9].

Lemma 1. *There are functions $\phi_N^{(2n)}$ such that*

$$x_0^{(N)} = 1 + \sum_{n=1}^{\infty} \phi_N^{(2n)} \tag{38}$$

where

$$\begin{aligned} \phi_N^{(2n)} &= \frac{(-1)^{n+1}}{(2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i z_i^{N+1} \frac{1}{z_1 z_{2n}} \\ &\times \prod_{k=1}^n Q(z_{2k-1}) Q(z_{2k-1}^{-1}) P(z_{2k}) P(z_{2k}^{-1}) \prod_{l=1}^{2n-1} \frac{1}{1 - z_l z_{l+1}}. \end{aligned} \tag{39}$$

Proof. Let $h(\xi)$ be a function defined on the unit circle $|\xi| = 1$, and let $h(\xi)$ have the Laurent expansion

$$h(\xi) = \sum_{n=-\infty}^{\infty} h_n \xi^n. \tag{40}$$

From this we define

$$[h(\xi)]_+ = \sum_{n=0}^{\infty} h_n \xi^n, \quad [h(\xi)]_- = \sum_{n=-\infty}^{-1} h_n \xi^n \quad \text{and} \quad [h(\xi)]'_+ = \sum_{n=1}^{\infty} h_n \xi^n. \tag{41}$$

From equations (41) it follows that

$$[h(\xi^{-1})]_- = [h(\xi)]'_+. \tag{42}$$

Equations (41) have the integral representations

$$[h(\xi)]_+ = \frac{1}{2\pi i} \lim_{\epsilon \rightarrow 0} \oint_{|\xi'|=1+\epsilon} d\xi' \frac{h(\xi')}{\xi' - \xi}, \tag{43}$$

$$[h(\xi)]_- = \frac{1}{2\pi i} \lim_{\epsilon \rightarrow 0} \oint_{|\xi'|=1-\epsilon} d\xi' \frac{h(\xi')}{\xi - \xi'} \tag{44}$$

and

$$\begin{aligned}
 [h(\xi)]'_+ &= [h(\xi)]_+ - \frac{1}{2\pi i} \oint_{|\xi|=1} d\xi \frac{h(\xi)}{\xi} \\
 &= \frac{1}{2\pi i} \xi \lim_{\epsilon \rightarrow 0} \oint_{|\xi'|=1+\epsilon} d\xi' \frac{h(\xi')}{\xi'(\xi' - \xi)}.
 \end{aligned}
 \tag{45}$$

We define

$$X_N(\xi) = \sum_{n=0}^{N-1} x_n^{(N)} \xi^n.
 \tag{46}$$

It has been proven by Wu [9] that the ratio (36) is given by

$$x_0^{(N)} = X_N(0)
 \tag{47}$$

where $X_N(\xi)$ is a function determined by equations (2.19a)–(2.20b) of [9] (with $Y(\xi) = 1$). These equations are

$$X_N(\xi) = P(\xi)\{[Q(\xi^{-1})]_+ + [Q(\xi^{-1})U_N(\xi)\xi^N]_+\} \tag{2.19a},
 \tag{48}$$

$$V_N(\xi^{-1}) = -(Q(\xi^{-1}))^{-1}\{[Q(\xi^{-1})]_- + [Q(\xi^{-1})U_N(\xi)\xi^N]_-\} \tag{2.20a},
 \tag{49}$$

$$X_N(\xi^{-1})\xi^N = Q(\xi)\{[P(\xi^{-1})\xi^N]_+ + [P(\xi^{-1})V_N(\xi)\xi^N]_+\} \tag{2.19b}
 \tag{50}$$

and

$$U_N(\xi^{-1}) = -(P(\xi^{-1}))^{-1}\{[P(\xi^{-1})\xi^N]_- + [P(\xi^{-1})V_N(\xi)\xi^N]_-\} \tag{2.20b}.
 \tag{51}$$

For our purposes we use equations (16), (42) and the equality $[Q(\xi^{-1})]_+ = 1$ to rewrite equations (48), (49) and (51) as

$$X_N(\xi) = P(\xi)\{1 + [Q(\xi^{-1})U_N(\xi)\xi^N]_+\},
 \tag{52}$$

$$V_N(\xi^{-1}) = -P(\xi^{-1})\{[Q(\xi^{-1})]_- + [Q(\xi^{-1})U_N(\xi)\xi^N]_-\}
 \tag{53}$$

and

$$U_N(\xi) = -Q(\xi)\{[P(\xi)\xi^{-N}]'_+ + [P(\xi)V_N(\xi^{-1})\xi^{-N}]'_+\}.
 \tag{54}$$

We define $V_N^{(1)}(\xi^{-1})$ by replacing $U_N(\xi)$ by 0 in equation (53). Thus

$$V_N^{(1)}(\xi^{-1}) = -P(\xi^{-1})[Q(\xi^{-1})]_-.
 \tag{55}$$

We note from equation (16) that $Q(0) = 1$. Thus, because $Q(\xi^{-1})$ is analytic for $|\xi| > 1$, we have

$$[Q(\xi^{-1})]_- = Q(\xi^{-1}) - Q(0) = Q(\xi^{-1}) - 1.
 \tag{56}$$

Therefore it follows from equations (16) and (56) that

$$-P(\xi^{-1})[Q(\xi^{-1})]_- = P(\xi^{-1}) - 1,
 \tag{57}$$

and thus equation (55) becomes

$$V_N^{(1)}(\xi^{-1}) = P(\xi^{-1}) - 1.
 \tag{58}$$

We define $U_N^{(1)}(\xi)$ by replacing $V_N(\xi^{-1})$ in (54) $V_N^{(1)}(\xi^{-1})$ as given by equation (58). Thus we find

$$U_N^{(1)}(\xi) = -Q(\xi)[P(\xi^{-1})P(\xi)\xi^{-N}]'_+.
 \tag{59}$$

It follows from equation (52) that $X_N^{(1)}(\xi)$ is given by

$$\begin{aligned} X_N^{(1)}(\xi) &= P(\xi)\{1 - [Q(\xi^{-1})Q(\xi)[P(\xi^{-1})P(\xi)\xi^{-N}]'_+\xi^N]_+\} \\ &= P(\xi)\left\{1 - \frac{1}{2\pi i} \lim_{\epsilon \rightarrow 0} \oint_{|\xi'|=1+\epsilon} d\xi' \frac{\xi'^N}{\xi' - \xi} Q(\xi'^{-1})Q(\xi')[P(\xi'^{-1})P(\xi')\xi'^{-xN}]'_+\right\}. \end{aligned} \tag{60}$$

Letting $\xi = 0$ in equation (60), and using $P(0) = 1$ and writing $X_N^{(1)}(0) = 1 + \phi_N^{(2)}$, we obtain

$$\begin{aligned} \phi_N^{(2)} &= -\frac{1}{2\pi i} \oint_{|\xi|=1} d\xi Q(\xi^{-1})Q(\xi)[P(\xi^{-1})P(\xi)\xi^{-N}]'_+\xi^{N-1} \\ &= -\frac{1}{2\pi i} \lim_{\epsilon \rightarrow 0} \oint_{|\xi_1|=1} d\xi_1 Q(\xi_1^{-1})Q(\xi_1) \frac{1}{2\pi i} \xi_1^N \oint_{|\xi_2|=1+\epsilon} d\xi_2 \frac{1}{\xi_2} \frac{1}{\xi_2 - \xi_1} P(\xi_2^{-1})P(\xi_2)\xi_2^{-N}. \end{aligned} \tag{61}$$

Thus, if we set

$$\xi_{2k+1} = z_{2k+1}, \quad \xi_{2k} = z_{2k}^{-1} \tag{62}$$

we obtain $\phi_N^{(2)}$ as given by equation (39).

We now calculate $V_N^{(2)}(\xi^{-1})$ by using equation (59) in equation (53):

$$\begin{aligned} V_N^{(2)}(\xi^{-1}) &= -P(\xi^{-1})\{[Q(\xi^{-1})]_- + [Q(\xi^{-1})U_N^{(1)}(\xi)\xi^N]\} \\ &= -P(\xi^{-1})[Q(\xi^{-1})]_- + P(\xi^{-1})[Q(\xi^{-1})Q(\xi)\xi^N[P(\xi^{-1})P(\xi)\xi^{-N}]'_+]_-. \end{aligned} \tag{63}$$

Next, we calculate $U_N^{(2)}(\xi)$ by using equation (63) in equation (54):

$$\begin{aligned} U_N^{(2)}(\xi) &= -(P(\xi))^{-1}\{[P(\xi)\xi^{-N}]'_+ + [P(\xi)V_N^{(2)}(\xi^{-1})\xi^{-N}]'_+\} \\ &= -Q(\xi)[P(\xi)P(\xi^{-1})\xi^{-N}]'_+ - Q(\xi)[P(\xi)P(\xi^{-1})\xi^{-N} \\ &\quad \times [Q(\xi)Q(\xi^{-1})\xi^N[P(\xi)P(\xi^{-1})\xi^{-N}]'_+]_+]. \end{aligned} \tag{64}$$

We will now calculate $X_N^{(2)}(\xi)$ from (52) and (64) as

$$\begin{aligned} X_N^{(2)}(\xi) &= P(\xi)\{1 + [Q(\xi^{-1})U_N^{(2)}(\xi)\xi^N]_+\} \\ &= P(\xi) - P(\xi)[Q(\xi^{-1})Q(\xi)[P(\xi)P(\xi^{-1})\xi^{-N}]'_+\xi^N]_+ \\ &\quad - P(\xi)[Q(\xi^{-1})Q(\xi)\xi^N[P(\xi)P(\xi^{-1})\xi^{-N} \\ &\quad \times [Q(\xi)Q(\xi^{-1})\xi^N[P(\xi)P(\xi^{-1})\xi^{-N}]'_+]_+]. \end{aligned} \tag{65}$$

Letting $\xi = 0$ in equation (65), we obtain $X_N^{(2)}(0) = 1 + \phi_N^{(2)} + \phi_N^{(4)}$:

$$\begin{aligned} \phi_N^{(4)} &= -\frac{1}{2\pi i} \oint_{|\xi|=1} d\xi Q(\xi^{-1})Q(\xi) \\ &\quad \times [P(\xi^{-1})P(\xi)\xi^{-N}[Q(\xi^{-1})Q(\xi)\xi^N[P(\xi^{-1})P(\xi)\xi^{-N}]'_+]_+]'_+\xi^{N-1} \\ &= -\frac{1}{(2\pi i)^4} \lim_{\epsilon \rightarrow 0} \oint_{|\xi_1|=1} d\xi_1 \xi_1^N Q(\xi_1^{-1})Q(\xi_1) \\ &\quad \times \oint_{|\xi_2|=1+\epsilon} d\xi_2 \frac{1}{\xi_2 - \xi_1} \xi_2^{-N-1} P(\xi_2^{-1})P(\xi_2) \oint_{|\xi_3|=1} d\xi_3 \frac{1}{\xi_3 - \xi_2} \xi_3^{N+1} Q(\xi_3^{-1})Q(\xi_3) \\ &\quad \times \oint_{|\xi_4|=1+\epsilon} d\xi_4 \frac{1}{\xi_4 - \xi_3} \xi_4^{-N-1} P(\xi_4^{-1})P(\xi_4). \end{aligned} \tag{66}$$

Using the change of variables (62) we obtain an equation agreeing with equation (39).

In general, we iteratively define (from equation (53))

$$V_N^{(n+1)}(\xi^{-1}) = -P(\xi^{-1})\{[Q(\xi^{-1})]_- + [Q(\xi^{-1})U_N^{(n)}(\xi)\xi^N]_-\}. \tag{67}$$

It then follows from equation (54) that

$$U_N^{(n)}(\xi) - U_N^{(n-1)}(\xi) = -Q(\xi^{-1})[P(\xi)P(\xi^{-1})\xi^{-N} \times [Q(\xi)Q(\xi^{-1})\xi^N [P(\xi)P(\xi^{-1})\xi^{-N} [Q(\xi)Q(\xi^{-1})\xi^N \dots]_-]_+]_+]_+, \tag{68}$$

where there are $2n - 1$ brackets. It now follows from equations (47) and (52) that $\phi_N^{(2k)}$ is

$$\phi_N^{(2k)} = -\frac{1}{2\pi i} \oint_{|\xi|=1} d\xi \xi^{N-1} Q(\xi)Q(\xi^{-1})[P(\xi)P(\xi^{-1})\xi^{-N} [Q(\xi)Q(\xi^{-1})\xi^N \times [P(\xi)P(\xi^{-1})\xi^{-N} [Q(\xi)Q(\xi^{-1})\xi^N \dots]_-]_+]_+]_+, \tag{69}$$

where there are $2k - 1$ brackets. By use of (62), one obtains equation (39). This ends the proof of the lemma. \square

3.2. Exponentiation

To complete the proof of the exponential form (17) we need to use (35), (36) and (38) to compute $F_N^{(2n)}$ as given in (19). We begin by defining a function

$$\tilde{F}_N^{(2n)} = \frac{(-1)^{n+1}}{n(2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i \prod_{j=1}^{2n} \frac{z_j^N}{1 - z_j z_{j+1}} \times \prod_{l=1}^n Q(z_{2l-1})Q(z_{2l-1}^{-1})P(z_{2l})P(z_{2l}^{-1}) \left(1 - \prod_{k=1}^{2n} z_k\right) \tag{70}$$

(we define $\tilde{F}_N^{(0)} = 0$). Clearly

$$F_N^{(2n)} = \sum_{k=N}^{\infty} \tilde{F}_k^{(2n)}. \tag{71}$$

Let $\phi_N^{(2n)}$ be given by equation (39) when $n \geq 1$ and let $\phi_N^{(0)} = 1$. We define the functions

$$\phi(\lambda) = \sum_{n=0}^{\infty} \phi_N^{(2n)} \lambda^n \tag{72}$$

and

$$\tilde{F}(\lambda) = \sum_{n=1}^{\infty} \tilde{F}_N^{(2n)} \lambda^n. \tag{73}$$

Clearly $\phi(0) = 1$ and $\tilde{F}(0) = 0$. We would like to show that

$$\phi(\lambda) = e^{\tilde{F}(\lambda)}. \tag{74}$$

It follows as a special case of (74) with $\lambda = 1$ that

$$X_N(0) = \exp \sum_{k=1}^{\infty} \tilde{F}_N^{(2k)}, \tag{75}$$

and hence it follows from equations (35) and (71) that

$$C_N = S_{\infty} \exp \sum_{k=N}^{\infty} \sum_{n=1}^{\infty} \tilde{F}_k^{(2n)} = S_{\infty} \exp \sum_{n=1}^{\infty} \sum_{k=N}^{\infty} \tilde{F}_k^{(2n)} = S_{\infty} \exp \sum_{n=1}^{\infty} F_N^{(2n)}. \tag{76}$$

This proves equation (19). It remains to show that equation (74) holds. Since $\phi(0) = 1$ and $\tilde{F}(0) = 0$, equation (74) is equivalent to the equation

$$\phi'(\lambda) = e^{\tilde{F}(\lambda)} \tilde{F}'(\lambda). \tag{77}$$

It follows from equations (72), (73) and (77) that equation (74) is equivalent to the following equation:

Lemma 2.

$$n\phi_N^{(2n)} = \sum_{l=1}^n l\tilde{F}_N^{(2l)}\phi_N^{(2n-2l)}. \tag{78}$$

Proof. It follows from (39) that the left-hand side of (78) is

$$\begin{aligned} n\phi_N^{(2n)} &= n(-1)^{n+1} \frac{1}{(2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i z_i^{N+1} \frac{1}{z_{2n}z_1} \\ &\quad \times \prod_{j=1}^n P(z_{2j})P(z_{2j}^{-1})Q(z_{2j-1})Q(z_{2j-1}^{-1}) \prod_{k=1}^{2n-1} \frac{1}{1-z_kz_{k+1}}, \end{aligned} \tag{79}$$

and the right-hand side is

$$\begin{aligned} &\sum_{l=1}^n l\tilde{F}_N^{(2l)}\phi_N^{(2n-2l)} \\ &= (-1)^n \frac{1}{(2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i \prod_{j=1}^{2n} \frac{z_j^N}{1-z_jz_{j+1}} \prod_{q=1}^n P(z_{2q})P(z_{2q}^{-1})Q(z_{2q-1})Q(z_{2q-1}^{-1}) \\ &\quad \times \left\{ \sum_{l=1}^{n-1} \frac{1}{1-z_1z_{2l}} \left(1 - \prod_{k=1}^{2l} z_k \right) (1 - z_{2l}z_{2l+1})(1 - z_{2n}z_1) \prod_{m=2l+2}^{2n-1} z_m - \left(1 - \prod_{k=1}^{2n} z_k \right) \right\}, \end{aligned} \tag{80}$$

where the product $\prod_{m=2l+2}^{2n-1} z_m$ is such that it equals 1 when $l = n - 1$. Note that the product $\prod_{j=1}^{2n}$ is symmetric both in even and in odd variables separately. Hence $1 - \prod_{k=1}^{2n} z_k$ can be rewritten (under integration) as

$$1 - \prod_{k=1}^{2n} z_k \equiv (1 - z_1z_{2n}) \left(1 + \sum_{q=1}^{n-1} \prod_{r=2}^{2q+1} z_r \right). \tag{81}$$

Next, note that the factor $\frac{1}{1-z_1z_{2l}}(1 - z_{2l}z_{2l+1})(1 - z_{2n}z_1) \prod_{m=2l+2}^{2n-1} z_m$ does not involve any of the variables $\{z_i\}_{i=2}^{2l-1}$. Hence the product $1 - \prod_{k=1}^{2l} z_k$ can be rewritten as

$$1 - \prod_{k=1}^{2l} z_k \equiv (1 - z_1z_{2l}) \left(1 + \sum_{q=1}^{l-1} \prod_{r=2}^{2q+1} z_r \right). \tag{82}$$

Then the relevant factor of the integrand of the right-hand side of equation (80) becomes

$$\begin{aligned} &(1 - z_{2n}z_1) \left\{ \sum_{l=1}^{n-1} (1 - z_{2l}z_{2l+1}) \left(1 + \sum_{q=1}^{l-1} \prod_{r=2}^{2q+1} z_r \right) \prod_{m=2l+2}^{2n-1} z_m - \left(1 + \sum_{q=1}^{n-1} \prod_{r=2}^{2q+1} z_r \right) \right\} \\ &= (1 - z_{2n}z_1) \left\{ \sum_{l=1}^{n-1} \left(1 + \sum_{q=1}^{l-1} \prod_{r=2}^{2q+1} z_r \right) \left(\prod_{m=2l+2}^{2n-1} z_m - \prod_{m=2l}^{2n-1} z_m \right) - \left(1 + \sum_{q=1}^{n-1} \prod_{r=2}^{2q+1} z_r \right) \right\}. \end{aligned} \tag{83}$$

After expansion of the first summand the right-hand side of (83) becomes

$$(1 - z_{2n}z_1) \left\{ \sum_{l=1}^{n-1} \prod_{m=2l+2}^{2n-1} z_m - \sum_{l=1}^{n-1} \prod_{r=2}^{2n-1} z_r - \left(1 + \sum_{q=1}^{n-1} \prod_{r=2}^{2q+1} z_r \right) \right\} \tag{84}$$

under integration. After summation (84) becomes

$$-n(1 - z_{2n}z_1) \prod_{r=2}^{2n-1} z_r, \tag{85}$$

which completes the proof. The proof of lemma 2 concludes the proof of equation (19). \square

4. The exponential expansion for $T > T_c$

In this section, we will prove that the functions $\widehat{F}_N^{(2n)}$ and $G_N^{(2n+1)}$ in (26) are given by (28) and (29). We will follow the procedure of section 2 of Wu [9]. When $T > T_c$, then $\alpha_1 < 1 < \alpha_2$ and $\widehat{\varphi}(z)$ has index 0. We define

$$b_n = \frac{1}{2\pi i} \oint_{|z|=1} \widehat{\varphi}(z) z^{-n-1} dz = a_{n-1}. \tag{86}$$

We further define

$$\mathbf{B}_{N+1} = \begin{pmatrix} b_0 & b_{-1} & \dots & b_{-N} \\ b_1 & b_0 & \dots & b_{1-N} \\ \vdots & \vdots & \ddots & \vdots \\ b_N & b_{N-1} & \dots & b_0 \end{pmatrix} \tag{87}$$

and

$$\widehat{D}_{N+1} = \det \mathbf{B}_{N+1}. \tag{88}$$

We note that if we remove the first row and the last column from \widehat{D}_{N+1} and use (86) we obtain D_N as defined by (8). Therefore we may write

$$D_N^{(+)} = \frac{D_N^{(+)}}{\widehat{D}_{N+1}} \widehat{D}_{N+1} = (-1)^N x_N^{(N)} \widehat{D}_{N+1}, \tag{89}$$

where the ratio $D_N^{(+)} / \widehat{D}_{N+1}$ is given as

$$\frac{D_N^{(+)}}{\widehat{D}_{N+1}} = (-1)^N x_N^{(N)} \tag{90}$$

and $\mathbf{x}^{(N)} = (x_0, x_1, \dots, x_N)$ satisfies

$$\mathbf{B}_{N+1} \mathbf{x}^{(N)} = \mathbf{d}^{(N)} \tag{91}$$

and $d_i^{(N)} = \delta_{i0}$. We indicate that the vector $\mathbf{x}^{(N)}$ has $N + 1$ entries by writing $x_N^{(N)}$. Since $\widehat{\varphi}(z)$ has index 0, it follows from Szegő's theorem that

$$\lim_{N \rightarrow \infty} (-1)^N \widehat{D}_N = \widehat{S}_\infty \tag{92}$$

where \widehat{S}_∞ is given by (27). Thus, exactly as for $T < T_c$,

$$(-1)^{N+1} \widehat{D}_{N+1} = \widehat{S}_\infty \prod_{n=N+1}^{\infty} \frac{\widehat{D}_n}{\widehat{D}_{n+1}}. \tag{93}$$

Furthermore, the ratio $\widehat{D}_n / \widehat{D}_{n+1}$ and the product

$$\prod_{n=N+1}^{\infty} \frac{\widehat{D}_n}{\widehat{D}_{n+1}} \tag{94}$$

may be treated exactly as in the case $T < T_c$ if we replace P and Q by \widehat{P} and \widehat{Q} . Thus we find

$$(-1)^{N+1} \widehat{D}_{N+1} = \widehat{S}_\infty \exp \sum_{n=1}^{\infty} \widehat{F}_{N+1}^{(2n)}, \quad (95)$$

and hence we have

$$D_N^{(+)} = -\widehat{S}_\infty x_N^{(N)} \exp \sum_{n=1}^{\infty} \widehat{F}_{N+1}^{(2n)}, \quad (96)$$

where we note that when $\alpha_1 = 0$, equation (30) holds.

It remains to calculate $x_N^{(N)}$. We will find $x_N^{(N)}$ by iterating the procedure of section 2 of Wu [9]. We define

$$X_N(\xi) = \sum_{n=0}^N x_n^{(N)} \xi^n, \quad (97)$$

and thus

$$x_N^{(N)} = \lim_{\xi \rightarrow 0} X_N(\xi^{-1}) \xi^N \quad (98)$$

where $X_N(\xi)$ is again defined by (48) to (51) with $P(\xi)$ and $Q(\xi)$ replaced by $\widehat{P}(\xi)$ and $\widehat{Q}(\xi)$. For convenience we rewrite (49), replacing ξ with ξ^{-1} , as

$$\begin{aligned} V_N(\xi) &= -\widehat{P}(\xi) \{ [\widehat{Q}(\xi)]'_+ + [\widehat{Q}(\xi) U_N(\xi^{-1}) \xi^{-N}]'_+ \} \\ &= \widehat{P}(\xi) - 1 - \widehat{P}(\xi) [\widehat{Q}(\xi) U_N(\xi^{-1}) \xi^{-N}]'_+. \end{aligned} \quad (99)$$

To obtain the first approximation $x_N^{(N)(1)}$ we replace $U_N(\xi)$ by 0 in (99), and write

$$V_N^{(1)}(\xi) = \widehat{P}(\xi) - 1. \quad (100)$$

We use this in (50) to give

$$X_N^{(1)}(\xi^{-1}) \xi^N = \widehat{Q}(\xi) [\widehat{P}(\xi^{-1}) \widehat{P}(\xi) \xi^N]_+. \quad (101)$$

Thus, letting ξ approach 0 and using (101) we obtain the first approximation $x_N^{(N)(1)}$, which we denote as $G_N^{(1)}$:

$$G_N^{(1)} = x_N^{(N)(1)} = \frac{1}{2\pi i} \oint_{|\xi|=1} \widehat{P}(\xi^{-1}) \widehat{P}(\xi) \xi^{N-1} d\xi. \quad (102)$$

We now compute the second approximation by using (100) in (51) to obtain

$$U_N^{(2)}(\xi^{-1}) = -\widehat{Q}(\xi^{-1}) [\widehat{P}(\xi^{-1}) \widehat{P}(\xi) \xi^N]_-. \quad (103)$$

We use (103) in (99) to find

$$V_N^{(2)}(\xi) = \widehat{P}(\xi) - 1 + \widehat{P}(\xi) [\widehat{Q}(\xi) \widehat{Q}(\xi^{-1}) \xi^{-N} [\widehat{P}(\xi^{-1}) \widehat{P}(\xi) \xi^N]_-]'_+. \quad (104)$$

Using this in (50) we obtain

$$\begin{aligned} X_N^{(2)}(\xi^{-1}) \xi^N &= \widehat{Q}(\xi) \{ [\widehat{P}(\xi^{-1}) \widehat{P}(\xi) \xi^N]_+ \\ &\quad + [\widehat{P}(\xi^{-1}) \widehat{P}(\xi) \xi^N [\widehat{Q}(\xi^{-1}) \widehat{Q}(\xi) \xi^{-N} [\widehat{P}(\xi^{-1}) \widehat{P}(\xi) \xi^N]_-]_+]_+ \}. \end{aligned} \quad (105)$$

Letting $\xi = 0$ in (105), we see that

$$x_N^{(N)(3)} = G_N^{(1)} + G_N^{(3)}, \quad (106)$$

where

$$G_N^{(3)} = \frac{1}{(2\pi i)^3} \lim_{\epsilon \rightarrow 0} \oint_{|z_1|=1} dz_1 z_1^N \widehat{P}(z_1) \widehat{P}(z_1^{-1}) \oint_{|z_2|=1-\epsilon} dz_2 \frac{z_2^{N+1}}{1-z_1 z_2} \widehat{Q}(z_2) \widehat{Q}(z_2^{-1}) \times \oint_{|z_3|=1} dz_3 \frac{z_3^N}{1-z_2 z_3} \widehat{P}(z_3) \widehat{P}(z_3^{-1}). \tag{107}$$

Continuing in the same way we may find

$$x_N^{(N)(2n+1)} = \sum_{k=0}^n G_N^{(2k+1)}, \tag{108}$$

and thus

$$D_N^{(+)} = -\widehat{S}_\infty \sum_{n=0}^\infty G_N^{(2n+1)} \exp \sum_{m=1}^\infty \widehat{F}_{N+1}^{(2m)} \tag{109}$$

where $\widehat{F}_N^{(2n)}$ is defined in (28), $G_N^{(2n+1)}$ is defined in (29) and \widehat{S}_∞ is defined by (27).

If we note that the $G_N^{(2n+1)}$ is the negative of the $G_N^{(2n+1)}$ of [17] and set $\alpha_1 = 0$, we have proven (6) of [17] with $G_N^{(2n+1)}$ given by (34) of [17].

5. The form factor expansion for $T < T_c$

We have showed in section 3 that the correlation function $D_N^{(-)}$ can be written in an exponential form given by (17) and (19). In this section we will show that $D_N^{(-)}$ can be written as a form factor expansion given by equations (20) and (21).

We wish to rewrite (17) as a form factor expansion and use an argument similar to that made by Nappi [11] to find the functions $f_N^{(2n)}$. To do this, we denote by a partition π of the number n a set of pairs $\pi = \{(n_i, m_i)\}_{i=1}^{v(\pi)}$ such that $n_i \neq n_j$ if $i \neq j$ and

$$\sum_{i=1}^{v(\pi)} n_i m_i = n. \tag{110}$$

We define $\mathcal{P}(n)$ to be the set of all such partitions. For instance, the partitions of the number 3 are

$$3 = \begin{cases} 1 \cdot 3, & v = 1 \\ 3 \cdot 1, & v = 1 \\ 1 \cdot 1 + 2 \cdot 1, & v = 2. \end{cases} \tag{111}$$

Thus the exponential of (17) may be expanded, and we find

$$f_N^{(2n)} = \sum_{\pi \in \mathcal{P}(n)} \prod_{i=1}^{v(\pi)} \frac{1}{m_i!} (F_N^{(2n_i)})^{m_i}, \tag{112}$$

where the sum is over the set of partitions $\mathcal{P}(n)$ of the number n . Thus $f_N^{(2n)}$ is the sum of all $2n$ dimensional integrals in (17). Explicitly

$$f_N^{(2n)} = \frac{(-1)^n}{(2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i z_i^N \prod_{j=1}^n Q(z_{2j-1}) Q(z_{2j-1}^{-1}) P(z_{2j}) P(z_{2j}^{-1}) \frac{1}{1-z_{2j-1} z_{2j}} \times \sum_{\pi \in \mathcal{P}(n)} \prod_{k=1}^{v(\pi)} (-1)^{m_k} \frac{1}{m_k! n_k^{m_k}} \prod_{p=1}^{m_k} \prod_{q=1}^{n_k} \frac{1}{1-z_{\sum_{r=1}^{k-1} 2m_r n_r + 2(p-1)n_k + 2q} z_{\sum_{r=1}^{k-1} 2m_r n_r + 2(p-1)n_k + (2q \oplus \pi, k) 1}} \tag{113}$$

where

$$2q \oplus_{\pi,k} 1 = \begin{cases} 2q + 1 & \text{if } q < n_k \\ 1 & \text{if } q = n_k. \end{cases} \tag{114}$$

We see that a partition π divides the integrand into $\sum_{k=1}^{v(\pi)} m_k$ loops, and that there are m_k loops of length n_k . As an illustration,

$$\begin{aligned} f_N^{(6)} = & -\frac{1}{(2\pi)^6} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^6 \oint_{|z_i|=1-\epsilon} dz_i z_i^N \prod_{j=1}^3 Q(z_{2j-1}) Q(z_{2j-1}^{-1}) P(z_{2j}) P(z_{2j}^{-1}) \\ & \times \frac{1}{1-z_1 z_2} \frac{1}{1-z_3 z_4} \frac{1}{1-z_5 z_6} \left(-\frac{1}{3!} \frac{1}{1-z_2 z_1} \frac{1}{1-z_4 z_3} \frac{1}{1-z_6 z_5} \right. \\ & \left. - \frac{1}{3} \frac{1}{1-z_2 z_3} \frac{1}{1-z_4 z_5} \frac{1}{1-z_6 z_1} + \frac{1}{2} \frac{1}{1-z_2 z_1} \frac{1}{1-z_4 z_5} \frac{1}{1-z_6 z_3} \right). \end{aligned} \tag{115}$$

The first term in the bracket of the right-hand side of (115) comes from $\pi_1 = \{(1, 3)\}$, the second from $\pi_2 = \{(3, 1)\}$ and the third from $\pi_3 = \{(1, 1), (2, 1)\}$. We would like to show that

$$\begin{aligned} f_N^{(2n)} = & \frac{1}{n!(2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i z_i^N \prod_{j=1}^n Q(z_{2j-1}) Q(z_{2j-1}^{-1}) P(z_{2j}) P(z_{2j}^{-1}) \frac{1}{1-z_{2j-1} z_{2j}} \\ & \times \sum_{\sigma \in S_n} \text{sign}(\sigma) \prod_{k=1}^n \frac{1}{1-z_{2k} z_{\sigma(2k-1)}}, \end{aligned} \tag{116}$$

where S_n is the group of permutations of the n elements $\{2i - 1\}_{i=1}^n$. For instance,

$$S_3 = \{(1)(3)(5), (13)(5), (15)(3), (35)(1), (135), (153)\} \tag{117}$$

where the loop (abc) means the permutation $a \rightarrow b \rightarrow c \rightarrow a$. We say that two permutations σ_1 and σ_2 in S_n are equivalent if for every loop in σ_1 there is one and only one loop of equal length in σ_2 . Then σ_1 and σ_2 will also have the same signature. We write the equivalence class of an element σ as $[\sigma]$. We denote by E_n the set of equivalence classes of S_n . As an example, we have

$$E_3 = \{[(1)(3)(5)], [(13)(5)], [(135)]\}. \tag{118}$$

We will show that there is a bijection between $\mathcal{P}(n)$ and E_n . It is clear that $|\mathcal{P}(3)| = |E_3| = 3$. We will now prove the general case.

We will now calculate $|\sigma|$, the number of elements of the equivalence class of a permutation σ . We consider some $\sigma \in S_n$, and construct $[\sigma]$ as follows. We choose freely from n elements, and divide them into $\sum_{i=1}^v m_i$ loops such that there are m_i loops with n_i elements, without distinguishing between loops with the same number of elements. There are

$$\frac{n!}{\prod_{i=1}^v (n_i!)^{m_i} m_i!} \tag{119}$$

ways of doing this. There are $(n_i - 1)!$ ways of ordering a loop of n_i elements. Hence, there are

$$|\sigma| = \frac{n! \prod_{i=1}^v ((n_i - 1)!)^{m_i}}{\prod_{j=1}^v (n_j!)^{m_j} m_j!} = \frac{n!}{\prod_{i=1}^v n_i^{m_i} m_i!} \tag{120}$$

ways of choosing the elements. The signature of any element of the equivalence class $[\sigma]$ corresponding to π is

$$\text{sign}(\sigma) = (-1)^n \prod_{k=1}^{v(\pi)} (-1)^{m_k}. \tag{121}$$

If we identify every equivalence class with one of its representatives, then it follows from (113) that

$$f_N^{(2n)} = \frac{1}{n!(2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i z_i^N \prod_{j=1}^n Q(z_{2j-1}) Q(z_{2j-1}^{-1}) P(z_{2j}) P(z_{2j}^{-1}) \frac{1}{1 - z_{2j-1} z_{2j}} \times \sum_{\sigma \in E_n} \text{sign}(\sigma) |[\sigma]| \prod_{k=1}^n \frac{1}{1 - z_{2k} z_{\sigma(2k-1)}}. \tag{122}$$

Now (116) follows. By symmetry of the odd variables, (116) can be rewritten as

$$f_N^{(2n)} = \frac{1}{(n!)^2 (2\pi)^{2n}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n} \oint_{|z_i|=1-\epsilon} dz_i z_i^N \prod_{j=1}^n Q(z_{2j-1}) Q(z_{2j-1}^{-1}) P(z_{2j}) P(z_{2j}^{-1}) \times \left(\sum_{\sigma \in S_n} \text{sign}(\sigma) \prod_{k=1}^n \frac{1}{1 - z_{2k} z_{\sigma(2k-1)}} \right)^2. \tag{123}$$

Finally we note that the factor of the integrand of (123)

$$\sum_{\sigma \in S_n} \text{sign}(\sigma) \prod_{k=1}^n \frac{1}{1 - z_{2k} z_{\sigma(2k-1)}} \tag{124}$$

is zero if for any $i \neq j$, $z_{2i} = z_{2j}$ or $z_{2i-1} = z_{2j-1}$. Therefore

$$\sum_{\sigma \in S_n} \text{sign}(\sigma) \prod_{k=1}^n \frac{1}{1 - z_{2k} z_{\sigma(2k-1)}} = A_n \prod_{k=1}^n \prod_{l=1}^n \frac{1}{(1 - z_{2k-1} z_{2l})} \prod_{1 \leq p < q \leq n} (z_{2p-1} - z_{2q-1})(z_{2p} - z_{2q}). \tag{125}$$

By letting $z_{2n} = z_{2n-1} = 0$ we find that

$$A_n = A_{n-1}. \tag{126}$$

Since $A_1 = 1$, it follows that $A_n = 1$ for all n . Hence we obtain the desired result (19).

6. The form factor expansion for $T > T_c$

Above T_c , $D_N^{(+)}$ has a form factor expansion given by (31), where

$$f_N^{(2n+1)} = \sum_{k=0}^n G_N^{(2k+1)} \widehat{f}_{N+1}^{(2n-2k)} \tag{127}$$

and $\widehat{f}_N^{(2n)}$ is given by (116) but with P and Q replaced by \widehat{P} and \widehat{Q} . $G_N^{(2n+1)}$ is given by (29). Hence it follows from (116), (127) and (29) that

$$f_N^{(2n+1)} = -\frac{i}{(2\pi)^{2n+1}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n+1} \oint_{|z_i|=1-\epsilon} dz_i z_i^{N+1} \prod_{l=1}^{n+1} \widehat{P}(z_{2l-1}) \widehat{P}(z_{2l-1}^{-1}) \prod_{m=1}^n \widehat{Q}(z_{2m}) \widehat{Q}(z_{2m}^{-1}) \frac{1}{z_{2n+1}} \times \prod_{p=1}^n \frac{1}{1 - z_{2p-1} z_{2p}} \sum_{k=0}^n (-1)^k \frac{1}{(n-k)!} \frac{1}{z_{2n-2k+1}} \sum_{\sigma \in S_{n-k}} \text{sign}(\sigma) \times \prod_{q=1}^{n-k} \frac{1}{1 - z_{2q-1} z_{\sigma(2q)}} \prod_{s=n-k+1}^n \frac{1}{1 - z_{2s} z_{2s+1}}. \tag{128}$$

As an example,

$$\begin{aligned}
 f_N^{(5)} &= -\frac{i}{(2\pi)^5} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^5 \oint_{|z_i|=1-\epsilon} dz_i z_i^{N+1} \prod_{l=1}^3 \widehat{P}(z_{2l-1}) \widehat{P}(z_{2l-1}^{-1}) \\
 &\quad \times \prod_{m=1}^2 \widehat{Q}(z_{2m}) \widehat{Q}(z_{2m}^{-1}) \frac{1}{z_5} \frac{1}{1-z_1 z_2} \frac{1}{1-z_3 z_4} \\
 &\quad \times \left(\frac{1}{2} \frac{1}{z_5} \left(\frac{1}{1-z_1 z_2} \frac{1}{1-z_3 z_4} - \frac{1}{1-z_1 z_4} \frac{1}{1-z_2 z_3} \right) \right. \\
 &\quad \left. - \frac{1}{z_3} \frac{1}{1-z_1 z_2} \frac{1}{1-z_4 z_5} + \frac{1}{z_1} \frac{1}{1-z_2 z_3} \frac{1}{1-z_4 z_5} \right). \tag{129}
 \end{aligned}$$

Let $(i_1^{(k)}, \dots, i_n^{(k)}) = (1, \dots, n-k, n-k+2, \dots, n+1)$. It follows by symmetry that (128) can be rewritten as

$$\begin{aligned}
 f_N^{(2n+1)} &= -\frac{i}{(2\pi)^{2n+1}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n+1} \oint_{|z_i|=1-\epsilon} dz_i z_i^{N+1} \prod_{l=1}^{n+1} \widehat{P}(z_{2l-1}) \widehat{P}(z_{2l-1}^{-1}) \prod_{m=1}^n \widehat{Q}(z_{2m}) \widehat{Q}(z_{2m}^{-1}) \\
 &\quad \times \frac{1}{n+1} \sum_{r=0}^n (-1)^r \frac{1}{z_{2n-2r+1}} \prod_{p=1}^n \frac{1}{1-z_{2i_p^{(r)}} z_{2i_p^{(r)}}^{-1}} \\
 &\quad \times \frac{1}{n!} \sum_{k=0}^n (-1)^k \frac{1}{z_{2n-2k+1}} \sum_{\sigma \in S_n} \text{sign}(\sigma) \prod_{q=1}^n \frac{1}{1-z_{2i_q^{(k)}} z_{\sigma(2i_q^{(k)})}^{-1}}. \tag{130}
 \end{aligned}$$

In particular

$$\begin{aligned}
 f_N^{(5)} &= -\frac{i}{(2\pi)^5} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^5 \oint_{|z_i|=1-\epsilon} dz_i z_i^{N+1} \prod_{l=1}^3 \widehat{P}(z_{2l-1}) \widehat{P}(z_{2l-1}^{-1}) \prod_{m=1}^2 \widehat{Q}(z_{2m}) \widehat{Q}(z_{2m}^{-1}) \\
 &\quad \times \frac{1}{3} \left(\frac{1}{z_5} \frac{1}{1-z_1 z_2} \frac{1}{1-z_3 z_4} - \frac{1}{z_3} \frac{1}{1-z_1 z_2} \frac{1}{1-z_4 z_5} + \frac{1}{z_1} \frac{1}{1-z_2 z_3} \frac{1}{1-z_4 z_5} \right) \\
 &\quad \times \left\{ \frac{1}{2} \frac{1}{z_5} \left(\frac{1}{1-z_1 z_2} \frac{1}{1-z_3 z_4} - \frac{1}{1-z_1 z_4} \frac{1}{1-z_2 z_3} \right) \right. \\
 &\quad \left. - \frac{1}{2} \frac{1}{z_3} \left(\frac{1}{1-z_1 z_2} \frac{1}{1-z_4 z_5} - \frac{1}{1-z_1 z_4} \frac{1}{1-z_2 z_5} \right) \right. \\
 &\quad \left. + \frac{1}{2} \frac{1}{z_1} \left(\frac{1}{1-z_2 z_3} \frac{1}{1-z_4 z_5} - \frac{1}{1-z_3 z_4} \frac{1}{1-z_2 z_5} \right) \right\}. \tag{131}
 \end{aligned}$$

Since all permutations of the even elements are present in the sum $\sum_{k=0}^n$, symmetry allows the permutation of all even elements in the sum $\sum_{r=0}^n$. But the sum $\sum_{k=0}^n \sum_{\sigma \in S_n}$ may be rewritten as the sum $\sum_{\sigma \in S_{n+1}}$ of permutations of the odd elements. Therefore

$$\begin{aligned}
 f_N^{(2n+1)} &= -\frac{i}{(2\pi)^{2n+1}} \lim_{\epsilon \rightarrow 0} \prod_{i=1}^{2n+1} \oint_{|z_i|=1-\epsilon} dz_i z_i^{N+1} \prod_{l=1}^{n+1} \widehat{P}(z_l) \widehat{P}(z_l^{-1}) \prod_{m=1}^n \widehat{Q}(z_m) \widehat{Q}(z_m^{-1}) \\
 &\quad \times \frac{1}{n!(n+1)!} \left(\sum_{\sigma \in S_{n+1}} \text{sign}(\sigma) \frac{1}{z_{\sigma(2n+1)}} \prod_{q=1}^n \frac{1}{1-z_{\sigma(2q-1)} z_{2q}} \right)^2. \tag{132}
 \end{aligned}$$

An argument similar to the one given in section 5 shows that

$$\begin{aligned} \sum_{\sigma \in \mathcal{S}_{n+1}} \text{sign}(\sigma) \frac{1}{z_{\sigma(2n+1)}} \prod_{q=1}^n \frac{1}{1 - z_{\sigma(2q-1)} z_{2q}} \\ = \prod_{j=1}^{n+1} \frac{1}{z_{2j-1}} \prod_{k=1}^n \frac{1}{1 - z_{2j-1} z_{2k}} \\ \times \prod_{1 \leq l < m \leq n+1} (z_{2l-1} - z_{2m-1}) \prod_{1 \leq p < q \leq n} (z_{2p} - z_{2q}). \end{aligned} \quad (133)$$

Thus $f_N^{(2n+1)}$ is given by (32) as desired.

7. Discussion

The exponential and the form factor representations derived in this paper for $\langle \sigma_{0,0} \sigma_{0,N} \rangle$ and $\langle \sigma_{0,0} \sigma_{N,N} \rangle$ are considerably simpler than the corresponding representations which may be found in [10–14]. The representations of this paper must of course be equal to the corresponding results of [10–14] but, as mentioned in the introduction, even the equality of the form of $F_N^{(2)}$ found by Wu [9] with the form found by Cheng and Wu [6] has not been directly demonstrated in the literature. The form factor representations for $\langle \sigma_{0,0} \sigma_{N,N} \rangle$ proven here are in close correspondence with formulae given by Jimbo and Miwa [21] in their proof of the Painlevé VI representation of the diagonal Ising correlations. The connection which the form factor representations of this paper have with the PVI equation of [21] has been extensively investigated in [17]. However, the representations of this paper are valid also for $\langle \sigma_{0,0} \sigma_{0,N} \rangle$ and, as noted in the introduction, for much more general case which suggests that there are generalizations of [21] which have not yet been uncovered. In particular, the relation of $\langle \sigma_{0,0} \sigma_{0,N} \rangle$ to isomonodromic deformation theory remains to be investigated.

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