Elliptic solid-on-solid model’s partition function as a single determinant

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In this work we express the partition function of the integrable elliptic solid-on-solid model with domain-wall boundary conditions as a single determinant. This representation appears naturally as the solution of a system of functional equations governing the model’s partition function.

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INTRODUCTION

Several types of lattice models are exactly solvable in the sense that the summation defining their partition function can be expressed as a closed formula without any approximation. This is usually a highly non-trivial task but it has been achieved for certain models enjoying the gift of integrability [1]. Two-dimensional lattice models are rather special and among them we find the most notorious exactly solved models of Statistical Mechanics. For instance, the Ising model and the 8-vertex model. These models are corner stones of the modern theory of integrable systems and, in particular, a series of developments were due to Baxter’s ingenious works on the 8-vertex model [2–4]. In the course of studying eigenvectors of the symmetric 8-vertex model Baxter has introduced the so called solid-on-solid models or SOS models for short. They are also refereed to in the literature as interaction-round-a-face (IRF) models and they differ from vertex models in the way lattice interactions are characterized. While vertex models assign configuration variables to the edges of a rectangular lattice, SOS models associate configuration variables with lattice sites. In this way, the SOS model dual to Baxter’s 8-vertex model consists of an Ising type model with four-spin interaction as discussed in [3].

Boundary conditions are among the main ingredients when defining a lattice statistical system and the elliptic SOS model with domain-wall boundaries has received special attention recently. This special type of boundary conditions were firstly introduced by Korepin for the 6-vertex model [5] and subsequently translated to SOS models in [6]. Interestingly, for this particular type of boundary conditions the models’ partition functions can be written down explicitly as a closed formula [8,9], in contrast to the case with periodic boundary conditions. For the latter the solution still relies on the resolution of Bethe ansatz equations [10].

The 6-vertex model with domain-wall boundaries has found several applications, ranging from enumerative combinatorics [11] to the study of gauge theories [12], and the elliptic SOS model is not far behind. A series of works have been devoted to the study of its combinatorial properties [13] and relation to special polynomials [14]. These results are mainly due to Rosengren’s representation [8] for the model’s partition function as a sum of Frobenius type determinants which seem to generalize Izergin’s single determinant representation for the 6-vertex model [7].

Although a compact expression for the elliptic SOS model’s partition function has been found in [8], the possibility of expressing such partition function as a single determinant has eluded the researchers of the field so far. This is not only of interest for the computation of physical quantities but providing a definitive answer to this puzzle also shed new light onto the mathematical structure underlying elliptic integrable systems. This is precisely the purpose of this letter and in what follows we show how a single determinant representation can be derived from the analysis of special functional relations originated from the dynamical Yang-Baxter algebra.

THE MODEL

Write \( \mathcal{L}_n := \{1, 2, \ldots, n\} \) and let \((i, j) \in \mathcal{L}_{L+1} \times \mathcal{L}_{L+1}\) be 2-tuples describing a two-dimensional square lattice. Hence our lattice is formed by the juxtaposition of \( L \times L \) square cells which we shall simply refer to as faces. We assign a statistical weight \( w_{ij} \) to the face enclosed by the Cartesian coordinates \((i, j), (i, j+1), (i+1, j)\) and \((i+1, j+1)\). The configuration of a given face \( w_{ij} \) is characterized by variables \( \{h_{i,j}, h_{i,j+1}, h_{i+1,j}, h_{i+1,j+1}\} \) and the system’s partition function is defined as

\[
Z := \sum_{\{h_{i,j}\}} \prod_{i,j=1}^{L+1} w_{ij} \left( \begin{array}{cc} h_{i+1,j} & h_{i+1,j+1} \\ h_{i,j} & h_{i,j+1} \end{array} \right).
\]

The variable \( h_{i,j} \) is also referred to as height function and here \( h_{i,j} := \tau + n_{i,j} \gamma \) with \( \tau, \gamma \in \mathbb{C} \) and \( n_{i,j} \in \mathbb{Z} \). Also, here we consider that \( h_{i,j} \) and \( h_{i',j'} \) at neighboring sites can only differ by \( \pm \gamma \). The set \( \{h_{i,j}\} \) then contains height functions of allowed face configurations. Baxter’s elliptic SOS model has six allowed face configurations and
the respective statistical weights are given by,

\[
\begin{align*}
  w_{ij}(\tau \pm \gamma) &= [x + \gamma] \\
  w_{ij}(\tau \pm \gamma, \tau \pm 2\gamma) &= [\tau \pm \gamma] \frac{[x]}{[\tau]} \\
  w_{ij}(\tau \pm \gamma, \tau \pm \gamma) &= [\tau \pm x] \frac{[\gamma]}{[\tau]} ,
\end{align*}
\]

(2)

where \([x] := \sum_{n=-\infty}^{\infty} (-1)^{n-\frac{1}{2}} p^{n+\frac{1}{2}} e^{-(2n+1)x}\) for \(x \in \mathbb{C}\) and fixed elliptic nome 0 < \(p < 1\). The function \([x]\) corresponds to the Jacobi theta-function \(\vartheta_1(iz, \nu)\) with \(p = e^{i\pi \nu}\) according to the conventions of [13]. In order to completely define the partition function \(Z\) we also need to declare the boundary conditions being used. Here we shall consider boundary conditions of domain-wall type which corresponds to the assumptions \(h_{1,j} = h_{j,1} = \tau + (L + 1 - j)\gamma\) and \(h_{L+1,j} = h_{j,L+1} = \tau + (j - 1)\gamma\).

\[Z\]

ALGEBRAIC-FUNCTIONAL FRAMEWORK

The algebraic structure underlying the statistical weights (2) are nowadays well known. It consists of the elliptic quantum group \(\mathcal{E}_{p,\gamma}(\mathfrak{sl}_2)\), as described in [14, 17], and this enables the so called dynamical Yang-Baxter algebra to be used in the study of the partition function \(Z\). Here we shall adopt the procedure developed in [8] which exploits the dynamical Yang-Baxter algebra as a source of functional equations characterizing quantities of physical interest. We now write \(Z = Z_\tau(x_1, x_2, \ldots, x_L)\) in order to capture the dependence of our partition function with the relevant variables. The variables \(x_i \in \mathbb{C}\) will be referred to as spectral parameters while \(\tau\) will be called dynamical parameter. In addition to that \(Z\) also depends on inhomogeneity parameters \(\mu_i \in \mathbb{C}\) (1 ≤ \(i\) ≤ \(L\)) and an anisotropy parameter \(\gamma \in \mathbb{C}\). The latter are fixed from now on. Using the algebraic-functional framework we have shown in [8] that the partition function \(Z\) satisfies the following functional equation,

\[M_0 Z_\tau(X) + \sum_{i \in \{0,1,\ldots,L\}} N_i Z_{\tau+\gamma}(X_i) = 0 ,
\]

(3)

where \(X := \{x_i \in \mathbb{C} \mid 1 \leq i \leq L\}\) and \(X^o := X \cup \{x_o\}\). The coefficients in \(M_0\) explicitly read

\[
\begin{align*}
  M_0 &:= \frac{[\tau + \gamma]}{[\tau + (L + 1)\gamma]} \prod_{j=1}^{L} [x_0 - \mu_j] \\
  N_0 &:= \frac{[\tau + 2\gamma]}{[\tau + (L + 2)\gamma]} \prod_{j=1}^{L} [x_0 - \mu_j + \gamma] \prod_{j=1}^{L} \frac{[x_j - x_0 + \gamma]}{[x_j - x_0]} \\
  N_i &:= \frac{[\tau + 2\gamma]}{[\tau + (L + 2)\gamma]} \prod_{j=1}^{L} [x_i - \mu_j + \gamma] \\
  \quad \times \prod_{j=1, j \neq i}^{L} \frac{[x_j - x_i + \gamma]}{[x_j - x_i]} \quad \quad \quad i = 1, 2, \ldots, L.
\end{align*}
\]

We refer to \(M_0\) as equation type \(A\) due to its roots within the algebraic-functional method [8]. Using the same method we can also derive an equation of type \(D\) reading

\[\bar{M}_0 Z_{\tau+\gamma}(X) + \sum_{i \in \{0,1,\ldots,L\}} \bar{N}_i Z_{\tau}(X_i) = 0 ,
\]

(5)

with coefficients defined as

\[
\begin{align*}
  \bar{M}_0 &:= \prod_{j=1}^{L} [x_0 - \mu_j + \gamma] \\
  \bar{N}_0 &:= -\prod_{j=1}^{L} [x_0 - \mu_j] \prod_{j=1}^{L} \frac{[x_0 - x_j + \gamma]}{[x_0 - x_j]} \\
  \bar{N}_i &:= \frac{[\gamma][\tau + (L + 1)\gamma] + x_0 - x_i}{[x_0 - x_i][\tau + (L + 1)\gamma]} \prod_{j=1}^{L} [x_i - \mu_j] \\
  \quad \times \prod_{j=1, j \neq i}^{L} \frac{[x_i - x_j + \gamma]}{[x_i - x_j]} \quad \quad \quad i = 1, 2, \ldots, L.
\end{align*}
\]

Although each equation \((3)\) and \((5)\) can individually determine the partition function \((1)\), as shown in \([8]\), here we shall demonstrate how a determinant representation for \(Z\) follows from a particular combination of equations type \(A\) and \(D\).

DETERMINANT REPRESENTATION

In the recent paper [18] we have shown how functional equations with structure similar to \((3)\) and \((5)\) can be solved in terms of determinants. However, in order to tackle our present equations, namely \((3)\) and \((5)\), we need to generalize the mechanism of [18]. The reason for that is the dependence of \((3)\) and \((5)\) with the dynamical parameter \(\tau\). Hence we shall look for a suitable combination of our equations such that \(\tau\) no longer plays the role of variable. Now consider \((3)\) under permutations \(x_0 \leftrightarrow x_i\) for \(0 \leq i \leq L\). This operation leaves us with a set of \(L + 1\) equations involving \(Z_{\tau}(X_i)\) and \(Z_{\tau+\gamma}(X_i)\) for \(0 \leq i \leq L\).
Thus we can solve the resulting system of equations and, in particular, express $Z_{\tau+i\gamma}(X)$ as a combination of terms $Z_\tau(X_0^0)$. By substituting the result of this procedure in (6) we are then left with the functional relation

$$M_0 Z_\tau(X) + \sum_{i=1}^L \mathcal{N}_i Z_\tau(X_i^0) + \sum_{i=1}^L \mathcal{N}_i Z_\tau(X_i^0) = 0. \quad (7)$$

The coefficients of (7) explicitly read

$$M_0 := \prod_{j=1}^L \frac{[x_0 - x_j + \gamma][x_0 - \mu_j][x_0 - \mu_j + \gamma]}{[x_0 - x_j][x_0 - \mu_j + \gamma]} - \prod_{j=1}^L \frac{[x_0 - x_j + \gamma][x_0 - \mu_j]}{[x_0 - x_j]}$$

$$\mathcal{N}_i := \frac{\gamma[x_0 - x_i + \tau + (L + 1)\gamma]}{[\tau + (L + 1)\gamma][x_0 - x_i]} \times \prod_{j=1, j \neq i}^L \frac{[x_i - x_j + \gamma]}{[x_i - x_j]}$$

$$\mathcal{N}_i := \frac{\gamma[x_0 - x_i + \tau + (L + 1)\gamma]}{[\tau + (L + 1)\gamma][x_0 - x_i]} \prod_{j=1}^L [x_i - \mu_j] \times \prod_{j=1, j \neq i}^L \frac{[x_i - x_j + \gamma]}{[x_i - x_j]} \quad (8)$$

Compared to equations (3) and 5, we can readily see that $\tau$ no longer plays the role of variable and we fix it from this point on. Next we notice that permutations $x_0 \leftrightarrow x_l$ for $1 \leq l \leq L$, $x_0 \leftrightarrow x_m$ for $1 \leq m \leq L$ and simultaneous permutations $x_0 \leftrightarrow x_l$, $x_0 \leftrightarrow x_m$ for $1 \leq l < m \leq L$ yields new equations with extra terms of the form $Z_\tau(X_{1,0}^{0,0})$ where $X_{1,0}^{0,0} := X \cup \{x_0, x_{3L}\} \setminus \{x_1, x_2\}$, in addition to the ones already present in (7). The precise form of these new equations are not enlightening at the moment but it is important to remark that they form a closed system containing one term $Z_\tau(X)$, $L$ terms of type $Z_\tau(X_0^0)$, $L$ terms of $Z_\tau(X_i^0)$ and $\frac{L(L-1)}{2}$ terms of form $Z_\tau(X_0^0)$. On the other hand, we have $L$ equations produced by permutations $x_0 \leftrightarrow x_l$ ($1 \leq l \leq L$), another $L$ equations obtained from $x_0 \leftrightarrow x_m$ ($1 \leq m \leq L$) and $L(L-1)/2$ originated from the simultaneous permutations $x_0 \leftrightarrow x_l, x_0 \leftrightarrow x_m$ for $1 \leq l < m \leq L$. Thus we can solve the resulting system of equations and express each element $Z_\tau(X_0^0)$, $Z_\tau(X_i^0)$ and $Z_\tau(X_0^0)$ in terms of $Z_\tau(X)$. The proportionality factor will be a ratio of determinants according to Cramer’s rule. For instance, using this approach we can write $Z_\tau(X_0^0) = (\det(A_l)/\det(B)) Z_\tau(X)$ with given matrices $A_l$ and $B$ of dimension $d_L := L(L + 3)/2$. Although the matrices $A_l$ and $B$ exhibit local dependence with the variable $x_0$, the ratio $\det(A_l)/\det(B)$ is globally independent of $x_0$ since it corresponds to $Z_\tau(X_0^0)/Z_\tau(X)$. Interestingly, this same feature has already made its appearance in a different context. This is precisely the property allowing for the computation of path integrals through the localization method [19] (see also [20] for a review). Therefore, we can choose $x_0$ at our convenience and the inspection of the entries of $A_l$ and $B$ shows significant simplifications with the choice $x_0 = \mu_1 - \gamma$. Next we proceed with separation of variables and notice that the ratio $\det(B)/\det(B|_{\tau=-\gamma})$ is independent of $x_0$. Hence, we can conclude that $Z_\tau(X) \sim \det(B)/\det(B|_{\tau=-\gamma})$ and again the variable $x_0$ can be chosen at our will [21]. Here we shall fix $x_0 = \mu_1 - 2\gamma$ and the proportionality factor can be obtained from the asymptotic behavior presented in [3].

Following the above described procedure we are left with the solution

$$Z_\tau(X) = (-1)^L \left( \frac{(L+1)\gamma}{\tau + (L+2)\gamma} \right)^{d_L-1} \left( \frac{\tau + (L+2)\gamma}{L\gamma} \right)^{d_L} \prod_{i=1}^L [x_i - \mu_j] \prod_{k=1}^L [k\gamma] \left( \frac{\det(\Omega^{-1})}{\Omega^{-1}} \right), \quad (9)$$

where $\Omega_{red} := \Omega|_{\tau=-\gamma}$. In its turn the matrix $\Omega$ can be conveniently depicted as

$$\Omega = \begin{pmatrix} \mathcal{F} & \mathcal{I} & \mathcal{G} \\ \tilde{\mathcal{G}} & \mathcal{K} & \mathcal{J} \\ \mathcal{F} & \tilde{\mathcal{F}} & \mathcal{J} \end{pmatrix}, \quad (10)$$

where $\mathcal{F}$, $\tilde{\mathcal{F}}$, $\mathcal{G}$ and $\tilde{\mathcal{G}}$ are sub-matrices of dimension $L \times L$, $\mathcal{I}$ and $\mathcal{J}$ are of dimension $L \times L(L+1)/2$, $\tilde{\mathcal{G}}$ and $\mathcal{J}$ are of dimension $L(L-1)/2 \times L$, while the dimension of $\mathcal{K}$ is $L(L-1)/2 \times L(L-1)/2$. The matrices $\mathcal{F}$, $\tilde{\mathcal{F}}$ and $\mathcal{G}$
are diagonal with non-null entries given by

\[
J_{a,a} := \begin{bmatrix}
\gamma |x_\mu - x_\mu| & \prod_{k=1}^{L} [x_k - \mu_1] \\
\prod_{k=1}^{L} [x_k - \mu_1 + \gamma]
\end{bmatrix}
\]

\[
J_{a,a} := \begin{bmatrix}
\gamma |x_\mu - x_\mu| & \prod_{k=1}^{L} [x_k - \mu_1] \\
\prod_{k=1}^{L} [x_k - \mu_1 + \gamma]
\end{bmatrix}
\]

\[
G_{a,a} := \begin{bmatrix}
\gamma |x_\mu - x_\mu| & \prod_{k=1}^{L} [x_k - \mu_1] \\
\prod_{k=1}^{L} [x_k - \mu_1 + \gamma]
\end{bmatrix}
\]

On the other hand, the matrix \( \tilde{G} \) is a full-matrix with entries

\[
\tilde{G}_{a,b} := \begin{cases} 
\prod_{k=1}^{L} [x_k - \mu_1] & b = a \\
\prod_{k=1}^{L} [x_k - \mu_1 + \gamma] & \text{otherwise}
\end{cases}
\]

As for the remaining matrices it is convenient to introduce an index \( n: \mathbb{Z}_{>0} \times \mathbb{Z}_{>0} \to \mathbb{Z}_{>0} \). More precisely, we define \( n_{r,s} := s + L(r - 1) - \frac{r(r+1)}{2} \) for \( 1 \leq r < s \leq L \), and in this way we have

\[
K_{a,n_{r,s}} := \begin{bmatrix}
\gamma |x_\mu - x_\mu + \gamma | & \prod_{k=1}^{L} [x_k - \mu_1] \\
\prod_{k=1}^{L} [x_k - \mu_1 + \gamma]
\end{bmatrix}
\]

Next we turn our attention to the matrices \( \tilde{I} \) and \( \mathcal{J} \). The entries of \( \tilde{I} \) are then given by

\[
\tilde{I}_{n_{m,b}} := \begin{bmatrix}
\gamma |x_\mu - x_\mu + \gamma | & \prod_{k=1}^{L} [x_k - \mu_1] \\
\prod_{k=1}^{L} [x_k - \mu_1 + \gamma]
\end{bmatrix}
\]

while \( \mathcal{J} := 0 \) is a null-matrix. Lastly, we have the following expression for the entries of \( \mathcal{K} \),
The set of relations (9)-(10) defines an explicit single determinant formula for the partition function (11). Although the entries of $\Omega_{red}$ consist of straightforward simplifications of (11)-(10), it is worth remarking that for practical computations it might be more convenient to write $\det(\Omega \Omega_{red}^{-1})$ as the ratio $\det(\Omega) / \det(\Omega_{red})$. In this way one avoids computing the inverse of $\Omega_{red}$ and evaluating the product $\Omega \Omega_{red}^{-1}$.

**CONCLUDING REMARKS**

In the present paper we have obtained a novel representation for the partition function of the elliptic SOS model in terms of a single determinant. This result addresses a long-standing question in the field and confirms the existence of such representations. In the limit $p \to 0$, where $[x]$ degenerates into a trigonometric function, followed by the limit $\tau \to \infty$; the partition function (11) reduces to that of the six-vertex model with domain-wall boundaries studied in [5, 7]. In contrast to the $L \times L$ matrix determinant representation found in [7], our solution consists of a determinant of a $L(L + 3)/2 \times L(L + 3)/2$ matrix. However, it is also important to notice that the determinant of $\gamma$ is taken over a full-matrix, while in our case we have a sparse matrix. In this way one might expect that (9) is still liable to simplifications. Another interesting aspect of the representation (9) is related to the possibility of taking the homogeneous limit. In our case the partial homogeneous limit $\mu_i \to \mu$ can be obtained trivially in contrast to Izergin’s representation for the six-vertex model.

Here we have singled out one particular possibility of determinant representation originated from the algebraic-functional framework. Alternative determinant representations are also possible and we plan to investigate them in a future publication [21]. Moreover, it is quite remarkable the similarity between the roles played by the variables $x_0$ and $x_0$ here and the mechanism employed in the localization method for the evaluation of path integrals [20]. This point certainly deserves further studies and we hope to address it in a future publication.

### TABLE I. Two sets of numerical values for the parameters.

| Parameter | Set 1 | Set 2 |
|-----------|-------|-------|
| $x_1$; $\mu_1$ | 0.4327; 0.6745 | 0.8919; 2.5449 |
| $x_2$; $\mu_2$ | 1.0715; 0.4129 | 0.7233; 1.8734 |
| $x_3$; $\mu_3$ | 1.7481; 3.3385 | 0.1519; 1.2745 |
| $x_4$; $\mu_4$ | 2.2738; 3.1245 | 0.4388; 2.0178 |
| $x_5$; $\mu_5$ | 2.1415; 1.9715 | 2.6662; 3.0089 |
| $\gamma$ | 0.6512 | 0.1219 |
| $\tau$ | 0.1743 | 0.2759 |
| $p$ | 0.3116 | 0.4421 |

### TABLE II. Numerical comparison using Set 1.

| $L$ | Definition (11) | Representation (9) |
|-----|----------------|-------------------|
| 2   | 0.00057111882715 | 0.00057111882715 |
| 3   | 6.07562588434218 i | 6.07562588434047 i |
| 4   | 6195.98835673588 | 6195.98835673588 |
| 5   | 139.817171384552 i | 139.817171384640 i |

### Numerical checks

From definition (11) we find $Z_{\tau} = [\gamma][\gamma + \mu_1 + x_1]/[\gamma + \mu_1 + x_1]$ for $L = 1$. This is precisely the result obtained from our representation (9) with the help of summation formulæ for Jacobi theta-functions. For $L > 1$ we can easily compare numerically the value of the partition function computed from the definition (11) with the one obtained from our representation (9). This provides extra support for the validity of our results. Numerical evaluations have been performed with Mathematica and in Table I one can find two sets of randomly chosen values for the model’s parameters. Tables I and II contain numerical comparisons using Set 1 and Set 2 respectively for $2 \leq L \leq 5$.

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TABLE III. Numerical comparison using Set 2.

| L  | Definition (1)  | Representation (9) |
|----|----------------|--------------------|
| 2  | 0.230323036097803 | 0.230323036097803 |
| 3  | 0.202679526300981 i | 0.202679526300981 i |
| 4  | 2.659105034549285  | 2.659105034415262  |
| 5  | 1478.397210835060 i| 1478.397210823134 i|

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