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Equivalence of S_3 -invariant lattice model
and model of vertex-face type

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Abstract

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We show that the S_3 -invariant model proposed in [2] is equivalent to the vertex-face model with two kinds of Boltzmann weights, which appeared to satisfy the generalized Yang-Baxter equation. A more general solution of this equation is constructed in the framework of some appropriate ansatz. This solution depends on the continuous parameter q . The initial model is a particular case of $q = \pm i e^{\mp 2\pi/3i}$. The integrability of this model is discussed.

Аннотация

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Показано, что S_3 -инвариантная модель, предложенная в работе [2] эквивалентна вершинно-граневой модели с Больцмановскими весами двух типов, которые удовлетворяют обобщенному уравнению Янга-Бакстера. Построено более общее решение этого уравнения в рамках некоторого анзаца. Это решение зависит от непрерывного параметра q . Исходная модель является частным случаем $q = \pm i e^{\mp 2\pi/3i}$. Интегрируемость этой модели обсуждается.

1. Introduction

Two-dimensional statistical systems and critical phenomena have been under active study over the recent years. There are two basic alternative formulations of lattice models: vertex and face (or interaction-round-face (IRF)) ones. The mixed-type formulations are also possible. The equivalence of two different types of the models may often be useful if the solution to one of them is known. For instance, one can recollect the reformulation of the eight-vertex model as an Ising model with interaction with two and four spins, the equivalence of Potts model and six-vertex model with two sub-lattices and as a particular case the critical Potts model and pure six-vertex model, the equivalence of homogeneous Ashkin-Teller model and eight-vertex model, etc.[1]. The reformulation of some initial model may also be useful because the equivalent one may allow some generalizations which can be interesting independently.

In ref. [2] the S_3 -symmetrical model appeared as interesting generalization of Z_N -symmetrical chiral Potts model [4] for the case of non-Abelian discrete symmetry and there was obtained a solution of the star-triangle equation. The Boltzmann weights have a form resembling, to some extent those of Potts model. So, it seems that in this case it is possible to apply the procedure similar to Potts model one. This procedure leads to the model equivalent to the S_3 -invariant model. The Boltzmann weights of this model appeared to satisfy a new equation (see (3.18)) which resembles star-triangle equation with additional indices on edges. On the other hand, the authors of ref. [5] proposed the generalized Yang-Baxter equation allowing one to construct commuting two-layer transfer matrices. It appears that one can use the equation (3.18) in the same way. The solution to this equation in an appropriate ansatz is obtained. It depends on some continuous parameter q which resembles the deformation parameter in quantum groups and associated statistical systems.

In section 2 the initial model is formulated, some predictions, conjectured in ref. [2] about its phase structure are presented and the free energy in thermodynamic limit is found by the method proposed in ref. [3]. In section 3 the equivalent model is constructed. A generalized solution of this equation is obtained. The construction of the commuting family of two-layer transfer matrices is discussed.

2. S_3 -invariant model

The action of the S_3 -invariant model has the following form:

$$-S(g) = \sum_{\langle i,j \rangle} \sum_r \beta_r \chi_r(g_i^{-1} g_j) + \sum_{\langle i,k \rangle} \sum_r \bar{\beta}_r \chi_r(g_i^{-1} g_k). \quad (2.1)$$

Here χ_r are the characters of the S_3 group corresponding to three irreps ($r = 0, r = 1, r = 2$ are trivial, one-dimensional and two-dimensional irreps). In first (second) term in the r.h.s. of (2.1) the sum is over horizontal (vertical) links of the neighboring sites on the lattice. The constants β_r and $\bar{\beta}_r$ are not equal in general and therefore the model may have an anisotropy. It should be stressed that the line $2\beta_1 = \beta_2$ corresponds to isotropic 6-state Potts model and on the line $\beta_2 = 0$ the model becomes the Ising one. In addition, there are some features of 3-state Potts model which will be used below. So, the S_3 -invariant lattice system incorporates Ising and Potts models. On using some correlator inequalities it was conjectured in ref. [2] that isotropic ($\beta_r = \bar{\beta}_r$) model had three phases. The first phase possesses an unbroken S_3 -invariance and spontaneously broken dual S_3 -invariance in the branch of small β_1 and β_2 . The second phase has unbroken Z_3 -symmetry and dual Z_2 -symmetry when $\beta_1 \rightarrow \infty$ and $\beta_2 \rightarrow 0$ and the third one possesses spontaneously broken S_3 -symmetry when $\beta_2 \rightarrow \infty$. There is a definite point $(\beta_1, \beta_2) \doteq (1/8 \ln 2 + 1/6 \ln(1 + 3/\sqrt{2}), 1/3 \ln(1 + 3/\sqrt{2}))$ which seems to be a tricritical one where all three phases meet and the model becomes solvable exactly. This critical point is the projection of the one-parameter critical line in anisotropic case. The model on this critical line will be considered in this section. The corresponding Boltzmann weights for horizontal and vertical links have the following matrix structure resulting from the requirement of symmetry: $W_{i,j} = W(g_i^{-1} g_j)$ and $\bar{W}_{i,j} = \bar{W}(g_i^{-1} g_j)$ where $W(g) = f_r$, $\bar{W}(g) = \bar{f}_r$ and r is the order of group element g and $f_0(u) = 2u(2u^2 - 1), f_1(u) = 2(2 - u^2), f_2(u) = 2u(2 - u^2)$ and $\bar{f}_r(u) = f_r(\sqrt{2}/u)$. W -weight has a form:

$$W(u) = \begin{pmatrix} W_{\text{potts}}(u) & f_1(u)E \\ f_1(u)E & W_{\text{potts}}(u) \end{pmatrix}, \quad (2.2)$$

where

$$(W_{\text{potts}}(u))_{\overline{ij}} = (f_0(u) - f_2(u))\delta_{\overline{ij}} + f_2(u), \quad (2.3)$$

and $E_{\vec{i}\vec{j}} = 1$, $\vec{i}\vec{j} = (1, 2, 3)$, $\bar{W}(u) = W(\sqrt{2}/u)$. The $W(\bar{W})$ weights satisfy the star-triangle equation

$$\sum_l \bar{W}_{i,l}(u) \bar{W}_{j,l}(v) W_{k,l}(uv) = 3\sqrt{2} \bar{W}_{i,j}(uv) W_{i,k}(v) W_{j,k}(u). \quad (2.4)$$

This model possesses crossing invariance that is the equality $Z(u) = \bar{Z}(\sqrt{2}/u)$ for statistical sum Z defined on the square lattice is valid. In the region $1 \leq u \leq \sqrt{2}$ all Boltzmann weights are non-negative and the model is physical. The statistical sum for cyclic boundary conditions may be easily found in thermodynamic limit by the "inversion" method [3]. Let T and $\bar{T}$ be transfer matrices

$$T_{j_1 \dots j_N}^{j'_1 \dots j'_N} = \prod_{i=1}^N \bar{W}_{j_i, j'_i} W_{j'_i, j_{i+1}} \quad (2.5)$$

$$\bar{T}_{j_1 \dots j_N}^{j'_1 \dots j'_N} = \prod_{i=1}^N W_{j'_i, j_i} \bar{W}_{j_i, j'_{i+1}}, \quad (2.6)$$

where $j_{N+1} = j_1$ and N is even. The following expressions take place as a consequence of the star-triangle equation:

$$T(u) \bar{T}(v) = T(v) \bar{T}(u) \quad (2.7)$$

$$\bar{T}(v) T(u) = \bar{T}(u) T(v) \quad (2.8)$$

and $\bar{T} = X_+ T = T X_+$ where X_+ is a spin-shift operator. Using the equality $W_{i,j}(\sqrt{2}) = 6\sqrt{2}\delta_{i,j}$ and eq.(2.4) one can obtain the functional equation

$$T(u) \bar{T}(\sqrt{2}u) = \phi(u)^{2N} (I + H(u)), \quad (2.9)$$

where I in the r.h.s. of (2.9) is the identity matrix, $\phi(u) = \sqrt{288}(2-u^2)(2u^2-1)/u^2$ and

$$H_{j_1 \dots j_N}^{j'_1 \dots j'_N} = \prod_{i=1}^N X(j_i, j_{i+1}; j'_i, j'_{i+1}) \quad (2.10)$$

$$X(i, j; k, l) = 1/\phi(u)^2 \sum_p \bar{W}_{i,p}(u) W_{j,p}(u) W_{k,p}(\sqrt{2}u) \bar{W}_{l,p}(\sqrt{2}u) \quad (2.11)$$

and

$$X(i, j; k, j) = 0 \quad (2.12)$$

if $i \neq k$. So, all diagonal elements of the matrix H are equal to 0. The remarkable fact is that in the strip $2^{-1/4} \leq u \leq 2^{1/4}$ all 27 different elements

of $X(i, j; k, l)$ are less than unity when $j \neq l$. So, in the thermodynamic limit ($N \rightarrow \infty$) H tends to zero. Therefore eq. (2.9) can be rewritten in the form

$$\lambda(u)\lambda(\sqrt{2}u) = \phi(u) \quad (2.13)$$

where $\lambda(u) = (\Lambda(u)\kappa^{1/2})^{1/2N}$, $\Lambda(u)$ and κ are eigenvalues of matrixes T and X_+ . Using Perron-Frobenius theorem one can conclude that κ is equal to 1. Equation (2.13) can be solved unambiguously taking into account that in the physical region $1 \leq u \leq \sqrt{2}$ the solution must be analytical. So, one has

$$\lambda(u) = \gamma \prod_{k=1}^{\infty} (g_{2k}(u)g_{2k-1}(1/u)) / (g_{2k+1}(u)g_{2k}(1/u)), \quad (2.14)$$

where $\gamma = 4 \cdot 3^{1/2} 2^{1/4}$ and $g_k(u) = 1 - u^2 2^{-k}$. The free energy per site is

$$-f \sim \lim_{N \rightarrow \infty} 1/N \ln(Z_N) = 2 \ln(\lambda) \quad (2.15)$$

As it has been stressed above this solution is valid in the strip $2^{-1/4} \leq u \leq 2^{1/4}$. Nevertheless, using the property of crossing-invariance $f(u) = f(\sqrt{2}/u)$ it may be continued analytically to the strip $2^{-1/4} \leq u \leq 2^{3/4}$ that evidently includes the physical one. From fig.1 it can be seen that neither pole nor zero is caught by this strip (white and black circles denote the poles and zeroes of λ)

3. Formulation of the equivalent model

The model described above may be sufficiently substantial. But on the critical line it is not so interesting from the viewpoint of physics. Unfortunately, the exact solution may exist only on this line. So, let us try to

formulate an equivalent model allowing further generalizations. Note in this case that the index j enumerating the rows and columns of W -weights can be presented as a pair of indices $(\alpha, \bar{j})$ where $\alpha = \pm 1$ and $\bar{j} = (1, 2, 3)$. The first index α will be termed an Ising index and the second one $\bar{j}$ will be termed a Potts one. As it can be seen from (2.2), the part of W -weights W_{potts} diagonal on the Ising indices has a form similar to the one for 3-state Potts model whereas the non-diagonal part does not depend on Potts indices. Let us present $W(u)$ in the following form :

$$W(u) = f_2(u)W'(u) \quad (3.1)$$

$$W_{potts}(u) = f_2(u)W'_{potts}(u) \quad (3.2)$$

$$W'_{potts}(u) = W'_{++}(u) = W'_{--}(u) = V(u)I + E \quad (3.3)$$

$$W'_{+-}(u) = W'_{-+}(u) = \sigma(u)E, \quad (3.4)$$

where

$$V(u) = 3(u^2 - 1)/(2 - u^2) \quad (3.5)$$

$$\sigma(u) = 1/u, \quad (3.6)$$

and similar functions $\bar{V}$ and $\bar{\sigma}$ may be introduced for the $\bar{W}$ -weight:

$$\bar{V}(u) = 3/2 (2 - u^2)/(u^2 - 1) \quad (3.7)$$

$$\bar{\sigma}(u) = u/\sqrt{2}. \quad (3.8)$$

The equality

$$V(u)\bar{V}(u) = 9/2 \quad (3.9)$$

is analogous to the critical condition in the Potts model. Then one can use a similar consideration which was used by Baxter to reformulate the critical Potts model as the six-vertex one (ref.[1]). Remind that the model is defined on the square lattice which will be called L . Let us consider medial lattice L_d with sites on the medial points of the links of the lattice L . The faces of the medial lattice L_d containing the sites of the lattice L were called elementary polygons by Baxter. The polygons having sites of the lattice L with the same Ising and Potts indices look like clusters in the ferromagnet. The interaction between the neighboring clusters depends only on the Ising indices. After

transformations similar to the case of the Potts model one can obtain the statistical sum

$$Z_N = (f_2(u) \bar{f}_2(u) \sqrt{3})^N \sum_{G_+, G_-} 3^{p/2} X(u)^l \bar{X}(u)^{\bar{l}} \sigma(u)^k \bar{\sigma}(u)^{\bar{k}}. \quad (3.10)$$

Here p is the number of boundaries (both inner and outer) of clusters, $G_{\pm}$ are all possible partitions on different clusters with the Ising indices ± 1 , $X(u) = V(u)/\sqrt{3}$, $\bar{X}(u) = \bar{V}(u)/\sqrt{3}$, k ($\bar{k}$) is the number of horizontal (vertical) links between the clusters with different Ising indices. Then let us introduce arrows on each edge of the clusters in such a way that each cluster has one of two possible orientations as shown in fig.2.

fig.2

The lattice L in fig.2 is turned by $\pi/4$ and is shown by dotted lines. If one relates the factor z^α with each corner of the cluster, where $\alpha = \pm\pi/2$ is the rotation angle of the arrow in this corner then the full contribution of the clockwise and counterclockwise rounds must be equal to

$$q + 1/q = \sqrt{3}, \quad (3.11)$$

where $q = z^{2\pi}$. Then the summation over partitions $G_{\pm}$ may be replaced by the summation over all possible covers with arrows with only one condition

that two arrows should go into and two arrows go out of each site of the medial lattice L_d (the so-called ice condition).

Now we can "forget" about lattice L and consider a new model defined on the lattice L_d with new weights for each site of the L_d . There are two kinds of these weights, $R_{\alpha,\beta}(i, j; k, l)$ and $\bar{R}_{\alpha,\beta}(i, j; k, l)$ (fig.3), corresponding to the sites of the lattice L_d lying on the "horizontal" and "vertical" edges of the lattice L (on fig.2 "vertical" and "horizontal" axes are turned by $\pi/4$).

$$R_{\alpha\beta}(i, j; k, l) = \begin{array}{c} l \\ \hline \alpha \\ \hline \hline \hline \hline \hline \hline \\ i \end{array} \begin{array}{c} j \\ \hline \hline \hline \hline \hline \hline \\ k \end{array} \quad \bar{R}_{\alpha\beta}(i, j; k, l) = \begin{array}{c} l \\ \hline \hline \hline \hline \hline \hline \\ i \end{array} \begin{array}{c} \beta \\ \hline \hline \hline \hline \hline \hline \\ k \end{array} \begin{array}{c} j \\ \hline \hline \hline \hline \hline \hline \\ \alpha \end{array}$$

fig.3

These weights depend on the edge variables i, j, k, l corresponding to two possible directions of the arrows, and the Ising indices α and β of the opposite faces joining the site.

The allowed contributions for all possible arrow configurations are shown in figs.4 and 5 for R and $\bar{R}$ accordingly (the column on the left side of fig.4 and fig.5 shows the weights with the same Ising indices and the column on the right side shows the weights with the opposite ones). Let us introduce factors $q^{-1/2}$ and $q^{1/2}$ for the sites with the incoming arrow and the outgoing arrow lying on vertical lines (see fig. 4,5). Then one has a redefinition:

$$\begin{array}{ll} \omega_5 \rightarrow 1 + qX & \omega'_5 \rightarrow \sigma \\ \omega_6 \rightarrow 1 + 1/qX & \omega'_6 \rightarrow \sigma \\ \bar{\omega}_5 \rightarrow q + \bar{X} & \bar{\omega}'_5 \rightarrow q\bar{\sigma} \\ \bar{\omega}_6 \rightarrow 1/q + \bar{X} & \bar{\omega}'_6 \rightarrow 1/q\bar{\sigma}. \end{array} \quad (3.12)$$

All the notations used here are given in figs. 4,5. Let us divide all vertical links by $\bar{X}$ (the statistical sum will be multiplied by $\bar{X}^N$) and use $\bar{X}^{-1} =$

$=$ $= \omega_1 = 1$	$=$ $= \omega'_1 = \sigma$
$=$ $= \omega_2 = 1$	$=$ $= \omega'_2 = \sigma$
$=$ $= \omega_3 = X$	$=$ $= \omega'_3 = 0$
$=$ $= \omega_4 = X$	$=$ $= \omega'_4 = 0$
$=$ $+$ $= \omega_5 = q^{-1/2} + X q^{1/2}$	$=$ $= \omega'_5 = q^{-1/2} \sigma$
$=$ $+$ $= \omega_6 = q^{1/2} + X q^{-1/2}$	$=$ $= \omega'_6 = q^{1/2} \sigma$

fig.4

$$= \bar{\omega}_6 = q^{-1/2} + \bar{X} q^{1/2}$$

$$\omega_6 = 0$$

$2/3 X$. So, one obtains

$$Z_N = \rho(u)^N \tilde{Z}_N \quad (3.13)$$

$$\rho(u) = \sqrt{3} f_2(u) \bar{f}_2(u) \bar{X}(u), \quad (3.14)$$

where $\tilde{Z}_N$ is the statistical sum defined on the lattice in fig.6

for the model with the weights of two types (fig.3). Taking into account the above redefinition we finally obtain for R and $\bar{R}$ the following compact formulas:

$$R_{\alpha\beta} = (P + X(u) \tilde{P}) \delta_{\alpha,\beta} + \sigma(u) \tilde{P} \delta_{\alpha,-\beta} \quad (3.15)$$

$$\bar{R}_{\alpha\beta} = (P + 2/3 X(u) \tilde{P}) \delta_{\alpha,\beta} + 2/3 \bar{X}(u) \bar{\sigma}(u) \tilde{P} \delta_{\alpha,-\beta}. \quad (3.16)$$

Here P is a permutation matrix acting in the space of the edge variables, and the projector $\tilde{P}$ has the form

$$\tilde{P} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & q & 0 \\ 0 & 1/q & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (3.17)$$

It can be shown by a direct checking that the following equation is satisfied:

$$R_{\alpha\gamma}^{23}(u) \bar{R}_{\alpha\beta}^{13}(uv) R_{\beta\gamma}^{12}(v) = \sum_{\sigma} \bar{R}_{\alpha\sigma}^{12}(v) R_{\sigma\gamma}^{13}(uv) \bar{R}_{\sigma\beta}^{23}(u). \quad (3.18)$$

This equations is shown graphically in fig.7.

fig.6

fig.7

A similar equation with the weights of two types R and $\bar{R}$ without face indices is discussed in [5]. As a consequence of (3.18) the following two inversion relations are valid:

$$R_{\alpha\beta}^{12}(u) R_{\beta\alpha}^{21}(1/u) = I \quad (3.19)$$

$$\sum_{\sigma} \bar{R}_{\alpha\sigma}^{12}(u) \bar{R}_{\sigma\beta}^{21}(1/u) = \delta_{\alpha,\beta} I. \quad (3.20)$$

So, we have obtained the vertex-face type model satisfying generalized Yang-Baxter equation (3.18).

Now this equation may be considered independently. One can find its solution in the framework of the "ice condition" and following ansatz:

$$\begin{aligned} \omega_1 &= \omega_2 = 1 & \omega_3 &= b & \omega_5 &= h & \omega_6 &= f \\ \bar{\omega}_1 &= \bar{\omega}_2 = 1 & \bar{\omega}_3 &= \bar{b} & \bar{\omega}_5 &= \bar{h} & \bar{\omega}_6 &= \bar{f} \end{aligned} \quad (3.21)$$

$$\begin{aligned} \omega'_3 &= \omega'_4 = \bar{\omega}'_1 = \bar{\omega}'_2 = 0 \\ \omega'_1 &= \omega'_2 = \omega'_5 = \omega'_6 = \sigma(u) \\ \bar{\omega}'_3 &= \bar{\omega}'_4 = \bar{\sigma}(u) \end{aligned} \quad (3.22)$$

where

$$\begin{aligned} b(u) &= X(u) & \bar{b}(u) &= \zeta X(u) \\ h(u) &= 1 + q b(u) & \bar{h}(u) &= 1 + q \bar{b}(u) \\ f(u) &= 1 + 1/q b(u) & \bar{f}(u) &= 1 + 1/q \bar{b}(u). \end{aligned} \quad (3.23)$$

One has two defining relations:

$$\begin{aligned} &\zeta X(u)X(uv)X(v) + \\ &(q + q^{-1})X(u)X(v) + X(u) + X(v) - X(uv) = 0 \end{aligned} \quad (3.24)$$

$$\zeta (\bar{\sigma}(u) \sigma(uv) \bar{\sigma}(v) + 1) = 1 \quad (3.25)$$

The solution of these functional equations has the form

$$X(u) = \sqrt{\tau^2 + 1} (u^2 - 1) / (\tau^2 - u^2) \quad (3.26)$$

and

$$\begin{aligned} \sigma(u) &= 1/u & \bar{\sigma}(u) &= u/\tau \\ \zeta &= \tau^2 / (\tau^2 + 1) & (q + q^{-1}) &= \sqrt{\tau^2 + 1}. \end{aligned} \quad (3.27)$$

The expressions for R and $\bar{R}$ may be written in a form similar to (3.15)-(3.16) with the substitution $2/3 \rightarrow \zeta$. In addition, q is connected with τ by the last equation in (3.27) but (3.11) is not valid. Solution (3.15)-(3.16) becomes a particular case with $\tau = \sqrt{2}$. If the parameter τ is considered to be real then q is also real or lies on the unity circumference in a complex plane. Note, that in the case of (3.11) $q = \pm i e^{\mp 2\pi/3 i}$. This model has two kinds of transfer matrices $T(u)$ and $\bar{T}(u)$ shown in fig.8:

transfer-matrix T

transfer-matrix $\bar{T}$

fig.8

Using eqs.(3.18)-(3.20) one can show that in this case the equations similar to (2.7),(2.8) are valid. If the parameter q is real then all weights R and $\bar{R}$ are also real. Then the matrices of the form $T(u)\bar{T}(y(u))$, where $y(u)$ is any real function in the general case, are a commuting family of real matrices. If the parameter q belongs to the unit circle in a complex plane then one can easily see that

$$\bar{T}(u) = d(u) T^+(\tau/u), \quad (3.28)$$

where $d(u) = (b(u) \bar{b}(u))^{N/2}$. Then

$$\tilde{T}(u) = \tilde{T}(\tau/u) \quad (3.29)$$

$$[\tilde{T}(u), \tilde{T}(v)] = 0, \quad (3.30)$$

where

$$\tilde{T}(u) = 1/d(u) T(u) T^+(u). \quad (3.31)$$

So, the matrices $\tilde{T}(u)$ define the commuting family of hermitian crossing-invariant transfer matrices with the crossing parameter r which have a real spectrum. But in practice it may be more convenient to use another commuting family:

$$T(u)' = T(u)\bar{T}(1) \quad (3.32)$$

Conclusions

Let us note that the model described in section 3 has an attractive feature of conserving the edge colour as in the case of the six-vertex model. This fact could be helpful in applying Bethe Ansatz machinery. But up to now we have not succeeded to accomplish it. Nevertheless, a part of the eigenvalues of transfer-matrix $T(u)'$ can be found. In addition, there is a phase with antiferromagnetic ordering over the Ising indices of the ground state when the spectral parameter $u \rightarrow \infty$ and the asymptotics of the eigenvalue may be found by the Bethe method.

Note also that solution (3.15)-(3.16) was obtained in the framework of ansatz (3.21)-(3.23). Of course, it restricts the class of the solutions to equation (3.18). Further generalization could be done using the eight-vertex ansatz for weights R and $\bar{R}$.

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