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E_8 level two RSOS model

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Abstract

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In this paper we propose E_8 level=two Restricted Solid On Solid model.

Аннотация

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В настоящей работе мы предлагаем E_8 RSOS модель для уровня два.

1 Introduction

During last few years of the Yang–Baxter (YB) equation investigation the idea of transition from vertex models to face models, proposed in [1], appears to be rather fruitful. In vertex models the fluctuation variables are placed on the edges of two dimensional lattice. In case of dual objects (face models), variables lives on the faces, and Boltzmann weight is attached to a configuration round site. There is a regular method to obtain the face models from the vertex ones using properties of 3– and 6–j symbols [2] and the structure of vertex trigonometric R matrices [3].

The face models for classical infinite series are obtained in [4]. Note, that elliptic parametrization of Boltzmann weights is possible iff q is a root of unity, that is connected with the choise of affine Lie algebra level in corresponding Wess–Zumino–Witten–Novikov model (see references in [4]). These models are called Restricted Solid On Solid (RSOS) models.

In the present paper we deal with E_8 exceptional Lie algebra. Spectral decomposition for simplest 248(+1) dimensional module is not diagonal, so it is too difficult t calculate spectral functions. The space of states for corresponding face model under the re striction on level=2 is three dimensional, so the structure of YB equation itself is rather simple.

Here we present some arguments for our choise of admissibility matrix and Boltzmann weights for the face model. Uniqueness of W weights allows us to hope that our solution of YB equation corresponds to the E_8 level=2 RSOS model.

2 Deformed Affine Lie Algebrae

Let $\hat{\mathcal{G}}$ be an affine Lie algebra of type $X^{(1)}$, $\mathcal{G}$ be its simple part. $\{\alpha\} = \hat{\Pi}$ be a fundamental root system of $\hat{\mathcal{G}}$ and $\{\alpha\} = \Pi$ – a fundamental root system of $\mathcal{G}$, and

$$A_{\alpha\beta} = (\alpha, \beta^*) \tag{2.1}$$

be Cartan matrix for $\hat{\mathcal{G}}$ (or $\mathcal{G}$). Half of the sum of positive roots of $\mathcal{G}$ we denote as ρ:

$$\rho = \frac{1}{2}\sum_{\alpha>0}\alpha; \quad \rho^* = \frac{1}{2}\sum_{\alpha>0}\alpha^* \tag{2.2}$$

We also adopt the convention so that $|long \quad root|^2 = 2$.

Considering $\hat{\mathcal{G}}$ as the ring of Laurent polynomials in ξ with coefficients, belonging to the $\mathcal{G}$, one can write Cevalley basis of $\hat{\mathcal{G}}$ in the following form:

$$\begin{cases} \hat{e}_\alpha &= e_\alpha, \quad \hat{f}_\alpha = f_\alpha, \quad \hat{h}_\alpha = h_\alpha, \quad \alpha \in \Pi; \\ \hat{e}_0 &= \xi f_\theta, \quad \hat{f}_0 = \xi^{-1} e_\theta, \quad \hat{h}_0 = -h_\theta \end{cases} \tag{2.3}$$

where θ is the maximal root of $\mathcal{G}$ and ξ is the spectral parameter.

Denote the lattice of dominant weights of algebra $\mathcal{G}$ as $P_+ = \{\lambda\}$, and the irreducible module of $\mathcal{G}$ with higest weight λ as $r(\lambda)$. In order to distinguish fundamental weights of $\mathcal{G}$ shall us call the fundamental module(i) of lowest dimension as vector module(i), and other as tensor moduli.

As is implied by notations (2.3) $r(\lambda)$ is finite dimensional module of $\hat{\mathcal{G}}$:

$$r(\lambda) = \hat{r}(\lambda), \quad \lambda \in P_+ \tag{2.4}$$

Quantum deformation $\mathcal{U}_q(\hat{\mathcal{G}})$ can be described by deformation of Chevalley basis:

$$\begin{cases} [h, \hat{E}_\alpha] &= \alpha(h)\hat{E}_\alpha \\ [h, \hat{F}_\alpha] &= -\alpha(h)\hat{F}_\alpha \\ [\hat{E}_\alpha, \hat{F}_\beta] &= \delta_{\alpha\beta}\frac{[\alpha]}{[\alpha^2/2]} \end{cases} \tag{2.5}$$

$$\sum_{n=0}^{m=1-A_{\alpha\beta}} (-1)^n \binom{m}{n}_{q^{\alpha^2/2}} \hat{E}_\alpha^{m-n}\hat{E}_\beta\hat{E}_\alpha^n = 0$$

$$\binom{m}{n}_q = \frac{[m]!}{[n]![m-n]!} \tag{2.6}$$

where α, β belong to the fundamental root system of $\hat{\mathcal{G}}$. Hereafter we adopt the notation:

$$[u] = \frac{q^u - q^{-u}}{q - q^{-1}} \tag{2.7}$$

Finite dimensional moduli of $\mathcal{U}_q(\hat{\mathcal{G}})$ for general q can be recieved by quantization of classical moduli. As for simple part $\mathcal{G}$ and $\mathcal{U}_q(\mathcal{G})$, $r(\lambda) = r_q(\lambda)$ for any λ, and matrix elements of E_α and F_α are described by well known formulae for representations of $\mathcal{U}_q(A_1)$ [5]. For $\mathcal{U}_q(\hat{\mathcal{G}})$ it appears that for fundamental weights $\{\lambda\}$ $\hat{r}(\lambda) = \hat{r}_q(\lambda)$ if and only if $(\lambda, \theta) = 1$ (vector and spinor moduli, except for A_n seria).

For example, consider adjoint module. Starting from the higest weight vector V_θ one can obtain representations of one dimensional root subspaces

V_α and $n = rank(\mathcal{G})$ dimensional zero weight Cartan subspace, created by natural basis $\{H_\alpha\}$, $\alpha \in \Pi$:

$$(H_\alpha, H_\alpha) = 1, \quad (H_\alpha, H_\beta) = -\frac{(\alpha,\beta)}{\sqrt{[\alpha^2][\beta^2]}}, \quad \alpha \neq \beta \tag{2.8}$$

The next step is to construct a vector

$$H_\theta = \frac{1}{\sqrt{[2]}} F_\theta V_\theta$$

with properties, following from (2.5):

$$\begin{cases} F_\alpha H_\theta & = E_\alpha H_\theta = 0, \quad (\alpha,\theta) = 0 \\ F_{\alpha_\theta} H_\theta & = \sqrt{[2]} V_{-\alpha_\theta}, \quad (\alpha_\theta, \theta) = 1 \\ (H_\theta, H_\theta) & = 1 \end{cases} \tag{2.9}$$

Relations (2.9) determines H_θ uniquelly

$$H_\theta = \frac{\tilde{H}_{\alpha_\theta}}{[2]} + aW \tag{2.10}$$

where $\tilde{H}_{\alpha_\theta}$ is dual the vector to H_{α_θ} and zero weight vector W does not belong to the Cartan subspace. Parameter a is to be determined by the last relation of (2.9). The existence of vector W in a module of deformed affine Lie algebra (except for A_n) means that

$$\hat{r}_q(\theta) = r_q(\theta) \oplus r_q(0) \tag{2.11}$$

It is easy to see that for general case of fundamental weight λ : $\quad (\lambda, \theta) > 1$

$$\hat{r}_q(\lambda) = r_q(\lambda) \oplus \hat{r}_q(\lambda') \tag{2.12}$$

where λ' belongs to the Weil group orbit of $\lambda - \theta$.

3 Trigonometric R matrices and IRF models

Trigonometric R matrix in algebraic approach appears as intertwining operator for co-multiplication [3]:

$$R_{12}(x)\,\Delta_q\,(\hat{\mathcal{G}}) = \Delta_{1/q}(\hat{\mathcal{G}}) R_{12}(x) \tag{3.1}$$

$x^2 = \xi_1/\xi_2$; ξ_1, ξ_2 are the spectral parameters from definition (2.3).

We use the following form of co-multiplication:

$$\begin{cases} \Delta_q(h) & = h \otimes 1 + 1 \otimes h \\ \Delta_q(\hat{E}_\alpha) & = \hat{E}_\alpha \otimes q^{-\alpha/2} + q^{\alpha/2} \otimes \hat{E}_\alpha \\ \Delta_q(\hat{F}_\alpha) & = \hat{F}_\alpha \otimes q^{-\alpha/2} + q^{\alpha/2} \otimes \hat{F}_\alpha \end{cases} \tag{3.2}$$

$$\alpha \in \hat{\Pi}$$

Relation (3.1) is implied to be taken in representations 1 and 2 of $\mathcal{U}_q(\hat{\mathcal{G}})$. Some part of (3.2), corresponding to the semisimple part, is the Hopf algebra homomorphism, that allows one to build the theory of representations. In case of general moduli $\hat{r}_q(\mu)$ and $\hat{r}_q(\nu)$ one can write down the solution of (3.1) in the form

$$R_{\mu\nu}(x) = \sum_{\substack{\sigma_1,\sigma_2 \\ \sigma'_1,\sigma'_2}} \sum_{r_q(\lambda) \in \hat{r}_q(\mu) \otimes \hat{r}_q(\nu)} \rho^{\sigma'_1(\mu)\sigma'_2(\nu)}_{\sigma_1(\mu)\sigma_2(\nu)}(x,\lambda) P^{\sigma'_1(\mu)\sigma'_2(\nu)}_{\sigma_1(\mu)\sigma_2(\nu)}(\lambda) \tag{3.3}$$

where $\sigma(\mu), \sigma'(\mu)$ mean irreducible components of $\hat{r}_q(\mu)$, and

$$P^{\sigma'_1\sigma'_2}_{\sigma_1\sigma_2}(\lambda) =$$

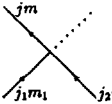
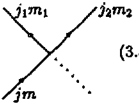
$$= \sum_{m_\lambda} < \sigma_1, m_1; \sigma_2, m_2 | \lambda, m_\lambda >_{1/q} < \lambda, m_\lambda | \sigma'_1, m'_1; \sigma'_2, m'_2 >_q \tag{3.4}$$

Here $|\lambda, m_\lambda >_q$ and $|\lambda, m_\lambda >_{1/q}$ are orthonormal vectors of module $r_q(\lambda)$, constructed with the help of $\Delta_q(\mathcal{G})$ and $\Delta_{1/q}(\mathcal{G})$ co-multiplications. Functions $\rho^{\sigma'_1\sigma'_2}_{\sigma_1\sigma_2}(x,\lambda)$ are to be found by treating equation (3.1) for affine generators.

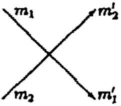
By this method trigonometric R matrices for all simple $((\lambda,\theta) = 1)$ moduli of all algebrae (except for E_8) have built [3,6]. R matrices for combined affine moduli (2.12) can be obtained by a fusion procedure. As for E_8 algebra, that has no vector module, equations for $\rho^{\sigma'_1\sigma'_2}_{\sigma_1\sigma_2}(x,\lambda)$ for adjoint⊗adjoint representation appear to be too complicated to be written out.

Solvable models with face interaction (Interaction Round Face) can be obtained from trigonometric R matrices using properties of quantum Clebsh-Gordon coefficients.

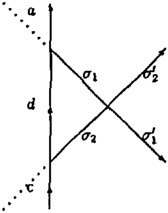
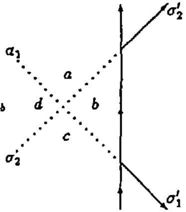
For the sake of simplicity introduce some graphical notations. Denote

$$< j_1, m_1; j_2, m_2 | j, m >= $$  $$=$$  $$(3.5)$$

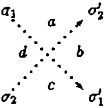
where auxiliary shaded lines carry index j_1 and separate areas of j and j_2.

$$(R_{\mu\nu})^{m_1' m_2'}_{m_1 m_2} = $$  $$(3.6)$$

where weights m_1, m_1' belong to the $\hat{r}_q(\nu)$ and m_2, m_2' — to the $\hat{r}_q(\nu)$.
Using formulae, described in the Appendix, one can find

 $$= \Sigma_b$$  $$(3.7)$$

where

 $$= W^{\sigma_1' \sigma_2'}_{\sigma_1 \sigma_2} \begin{pmatrix} a & b \\ d & c \end{pmatrix} | \, x \Big) =$$

$$= \sum_{\lambda} (-1)^{(\sigma_1 + \sigma_2 - \lambda, \rho^*)} \rho^{\sigma_1' \sigma_2'}_{\sigma_1 \sigma_2}(x, \lambda) * \qquad (3.8)$$

$$*\sqrt{\chi_d\chi_\lambda}\left\{\begin{matrix}\sigma_1 & \sigma_2 & \lambda\\ c & a & d\end{matrix}\right\}\sqrt{\chi_b\chi_\lambda}\left\{\begin{matrix}\sigma_1' & \sigma_2' & \lambda\\ a & c & b\end{matrix}\right\}$$

is the IRF Boltzmann weight. Here

$$\left\{\begin{matrix}a & b & c\\ \mu & \nu & \lambda\end{matrix}\right\}$$

is a quantum 6-j symbol with the same symmetry properties as the classical one, and the character

$$\chi_\lambda = \prod_{\alpha>0}\frac{[(\rho+\lambda,\alpha)]}{[(\rho,\alpha)]} \tag{3.9}$$

Total Boltzmann weight is

$$W_{\mu\nu}\left(\begin{matrix}a & b\\ d & c\end{matrix}\mid x\right) = \sum_{\sigma_1\sigma_2\sigma_1'\sigma_2'} W_{\sigma_1\sigma_2}^{\sigma_1'\sigma_2'}\left(\begin{matrix}a & b\\ d & c\end{matrix}\mid x\right) \tag{3.10}$$

Carrying the line of three Clebsh-Gordon coefficients through right and left hand sides of YB equation one obtains the face version of YB equation for $W_{\mu\nu}$.

Lattice variables of such models belong to the infinite lattice of dominant weights. These models are called Solid On Solid models. Boltzmann weights exist not for every configuration of states, bnt for such a, b, c, d that

$$d \in a\otimes\sigma_2, c \in d\otimes\sigma_1, b \in a\otimes\sigma_1', c \in b\otimes\sigma_2' \tag{3.11}$$

It is convenient to describe all admissible pairs of neighbouring states by matrix of admissibility

$$\bar{N}_{ab}^{\mu} = \begin{cases}1, & \text{if } b \in a\otimes\sigma(\mu) \text{ for some } \sigma;\\ 0, & \text{otherwise.}\end{cases} \tag{3.12}$$

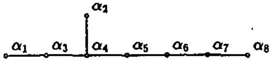
Taking q as the root of unity ($q^{h+l} = -1$, h–dual Coxeter number, l–an arbitrary integer number), one obtaines Restricted SOS model, connected with coset construction for Wess–Zumino–Witten–Novikov model of conformal field theory for algebra $\hat{\mathcal{G}}$ and level l. Admissibility matrix in this case *coincides with the matrix of conformal fusion rules:*

$$\bar{N}_{ab}^{\mu} \rightarrow N_{ab}^{\mu} \tag{3.13}$$

Note, that the restriction allows one to generalize tridonometric expressions for $W_{\mu\nu}$ to elliptic ones.

4 E_8 level=2 RSOS model

Cartan matrix for E_8 algebra describes by following Dynkin diagram:



where $\omega_8 = \theta$ and ω_1 have level=2, and other weights have higer levels. Since the simplest module of E_8 is adjoint module, so we deal with the combined module of $\mathcal{U}_q(\hat{\mathcal{G}})$:

$$\hat{r}_q(\omega_8) = r_q(\omega_8) \oplus r_q(\omega_0), \tag{4.1}$$

$r_q(w_0)$ is the trivial module.

The admissibility matrix is the sum of unity and fusion rules for level=2 (see Appendix):

$$N_{ab} = \begin{array}{c} \\ - \\ 0 \\ + \end{array} \begin{array}{c} \begin{array}{ccc} - & 0 & + \end{array} \\ \begin{pmatrix} 1 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} \end{array} \tag{4.2}$$

where '–' stands for ω_0, '0'–for ω_8, '+'– for ω_1.

Due to complexity of trigonometrical solution of YB equation it is easier to solve the face version of YB equation for the given N_{ab}. YB equation *and* unitarity condition appears to have only two solutions, corresponding to a symmetric and antysymmetric face projector decompositions. Relation (3.8) forbids antysummetric projectors, so there arises the unique solution of YB equation. Weights W appear to be symmetric with respect to horisontal and vertical reflections of states (see (3.8)), and with respect to simultaneous changing of "signes". So there are only eleven independed weights:

$$W\begin{pmatrix} + & + \\ + & + \end{pmatrix} | u \Big) = \frac{h(2\lambda - u)h(3\lambda + u)}{h(2\lambda)h(3\lambda)}$$

$$W\begin{pmatrix} + & 0 \\ + & + \end{pmatrix} | u \Big) = \varepsilon_1 \sqrt{\frac{h(4\lambda)}{h(2\lambda)}} \frac{h(u)h(2\lambda - u)}{h(\lambda)h(3\lambda)}$$

$$W\begin{pmatrix} + & 0 \\ 0 & + \end{pmatrix} | u \Big) = \frac{h(2\lambda - u)h(3\lambda - u)}{h(2\lambda)h(3\lambda)}$$

$$W\begin{pmatrix} + & + \\ + & 0 \end{pmatrix} u = \frac{h(\lambda+u)h(3\lambda+u)}{h(\lambda)h(3\lambda)}$$

$$W\begin{pmatrix} + & 0 \\ + & 0 \end{pmatrix} u = \epsilon_2\sqrt{\frac{h(\lambda)}{h(3\lambda)}}\frac{h(u)h(\lambda+u)}{h(\lambda)h(2\lambda)}$$

$$W\begin{pmatrix} + & 0 \\ 0 & 0 \end{pmatrix} u = \frac{h(\lambda+u)h(3\lambda-u)}{h(\lambda)h(3\lambda)}$$

$$W\begin{pmatrix} 0 & + \\ + & 0 \end{pmatrix} u = \frac{h(3\lambda+u)h(4\lambda+u)}{h(3\lambda)h(4\lambda)}$$

$$W\begin{pmatrix} 0 & 0 \\ + & 0 \end{pmatrix} u = \epsilon_1\sqrt{\frac{h(2\lambda)}{h(4\lambda)}}\frac{h(u)h(4\lambda+u)}{h(\lambda)h(3\lambda)}$$

$$W\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} u = \frac{h(3\lambda-u)h(4\lambda+u)}{h(3\lambda)h(4\lambda)} + \frac{h(u)h(\lambda+u)}{h(\lambda)h(4\lambda)}$$

$$W\begin{pmatrix} 0 & + \\ - & 0 \end{pmatrix} u = \frac{h(u)h(u-\lambda)}{h(\lambda)h(4\lambda)}$$

$$W\begin{pmatrix} + & 0 \\ 0 & - \end{pmatrix} u = \frac{h(\lambda+u)h(2\lambda+u)}{h(\lambda)h(2\lambda)} \tag{4.3}$$

where $\lambda = 1/8$ and

$$h(u) = \theta_1(u,\tau) = 2\sum_{n=0}^{\infty}(-1)^n e^{i\tau(n+\frac{1}{2})^2}\sin((2n+1)\pi u) \tag{4.4a}$$

or, using Baxter's notations,

$$\lambda = \frac{2I}{8}; \quad h(u) = H(u)\Theta(u) \tag{4.4b}$$

Using Inversion Transfer Matrix method [8], we found free energy of model for physical regime $u \in [-\lambda, 0]$:

$$z(u) = \lim_{N\to\infty} Z^{1/N^2} = z(-\lambda-u) = \frac{h(\lambda-u)h(2\lambda+u)}{h(\lambda)h(2\lambda)} \tag{4.5}$$

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Appendix A

Table of properties of 3– and 6–j symbols [2].

$$< \mu, m_\mu; \nu, m_\nu | \lambda, m_\lambda >_q =$$

$$=< \mu, -m_\mu; \lambda, m_\lambda | \nu, m_\nu >_q (-1)^{(\nu-\lambda-m_\mu,\rho^*)} q^{(m_\mu,\rho)} \sqrt{\frac{\chi_\lambda}{\chi_\nu}} =$$

$$=< \mu, -m_\mu; \nu, -m_\nu | \lambda, -m_\lambda >_{1/q} (-1)^{(\mu+\nu-\lambda,\rho^*)} =$$

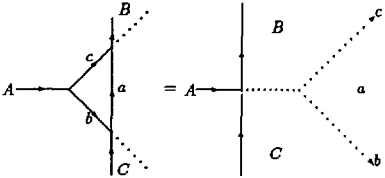
$$=< \nu, m_\nu; \mu, m_\mu | \lambda, m_\lambda >_{1/q} (-1)^{(\mu+\nu-\lambda,\rho^*)} \qquad (A.1)$$

Definition of 6–j symbols

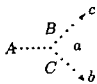
$$< j_1, j_1 j_3 (j_{23}), J | j_1 j_2 (j_{12}), j_3, J >=$$

$$= (-1)^{(j_1+j_2+j_3+J,\rho^*)} \ \overline{\chi_{12}\chi_{23}} \begin{Bmatrix} j_1 & j_2 & j_{12} \\ j_3 & J & j_{23} \end{Bmatrix} \qquad (A.2)$$

The used property of 6–j symbol:



where



$$= (-1)^{(C+B+c+b,\rho^*)}\ \overline{\chi_A \chi_a} \left\{ \begin{matrix} c & b & A \\ C & B & a \end{matrix} \right\} \qquad (A.3)$$

Appendix B

The easiest way to calculate level $= l$ fusion rule

$$a \otimes \mu = \sum_{b \in P_+^l} N_{ab}^{\mu} b \qquad (B.1)$$

is to use Walton's formula [7]

$$N_{ab}^{\mu} = \sum_{\substack{\gamma \in P_+ \\ \omega(\gamma,b)\cdot\gamma = b}} \epsilon(\omega(\gamma, b)) \bar{N}_{\bar{a}\bar{\gamma}}^{\bar{\mu}} \qquad (B.2)$$

Where "bar" denotes a simple part of affine weight, $\omega(\gamma, b)$ is the element of affine Weil group of level l and ϵ means the sign of Weil transformation.

The classical table of products for E_8 is

$$\begin{aligned} \omega_8 \otimes \omega_0 &= \omega_8 \\ \omega_8 \otimes \omega_8 &= \omega_0 \oplus \omega_8 \oplus \omega_1 \oplus \omega_7 \oplus 2\omega_8 \\ \omega_8 \otimes \omega_1 &= \omega_8 \oplus \omega 1 \oplus \omega_7 \oplus \omega_2 \oplus (\omega_1 + \omega_8) \end{aligned} \qquad (B.3)$$

Under restriction on level 2 the first relation does not change; in the second one ω_7 dies out for it has boundary level $= 3$; and $2\omega_8$ cancels ω_8. In the third relation ω_7 and ω_2 die out and $\omega_1 + \omega_8$ cancels ω_1. So level=2 fusion rules are

$$\begin{aligned} \omega_8 \otimes \omega_0 &= \omega_8 \\ \omega_8 \otimes \omega_8 &= \omega_0 \oplus \omega_1 \\ \omega_8 \otimes \omega_1 &= \omega_8 \end{aligned} \qquad (B.4)$$

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