

AN EXAMPLE OF FINITE DIMENSIONAL KAC ALGEBRAS OF KAC-PALJUTKIN TYPE

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ABSTRACT. An example of finite dimensional Kac algebras of Kac-Paljutkin type is given.

1. INTRODUCTION

Motivated by Pontryagin-Tannaka-Krein-Stinespring-Tatsuuma duality for locally compact groups, M.Enock and J.M.Schwartz introduced the notion of a Kac algebra and extended the duality to that of the category of Kac algebras. Any locally compact group is realized as a commutative Kac algebra and a cocommutative one, and conversely, any commutative (resp. cocommutative) Kac algebra comes from a locally compact group. However, to the author's knowledge, except for recent works of Majid [7, 8, 9] based on the matched pair introduced by Takeuchi [16], a number of examples of non-commutative and non-cocommutative Kac algebras do not seem to be known.

Before the general theory of Kac algebras, G.I.Kac and V.G.Paljutkin [5] considered a finite dimensional Kac algebra of a certain type. (They used the terminology "ring group".) They showed that the problem of constructing examples of the type is reduced to that of finding a family of unitary matrices satisfying certain conditions and gave a non-commutative and non-cocommutative 8 dimensional Kac algebra. (See also Masuoka [10].)

In the theory for subfactors initiated by V.Jones [4], A.Ocneanu [11] introduced the concept of a paragroup, which can be regarded as a quantization of groups, to classify subfactors. By using the so-called standard invariant equivalent to the paragroup, S.Popa classified subfactors under more general conditions. (See [13, 14].) It is known that the finite dimensional Kac algebras are characterized as special paragroups. (See David [1], Longo [6], Szymanski [15], and also Yamanouchi [17].)

Motivated by constructing non-commutative and non-cocommutative finite dimensional Kac algebras (as examples of paragroups), we shall give an example of finite dimensional Kac algebras of Kac-Paljutkin type by using the representation theory of extra-special p-groups and compute the dual structure.

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2. CONSTRUCTION OF FINITE DIMENSIONAL KAC ALGEBRAS

In order to fix notation, we first recall the definition of a finite dimensional Kac algebra. (We consider only the finite dimensional case.) For the general theory of Kac algebras, we refer to Enock and Schwartz [2, 3].

A finite dimensional Kac algebra \mathbf{K} is a quadruple $(M, \Gamma, \kappa, \varphi)$ such that

- (i) (M, Γ, κ) is an involutive finite dimensional Hopf-von Neumann algebra,
- (ii) φ is a faithful positive trace on M satisfying

$$(\iota_M \otimes \varphi)((1 \otimes y^*)\Gamma(x)) = \kappa((\iota_M \otimes \varphi)(\Gamma(y^*)(1 \otimes x))), \quad x, y \in M.$$

Here ι_M is the identity mapping of M . The linear functional φ is called a Haar weight of \mathbf{K} . Given a Kac algebra $\mathbf{K} = (M, \Gamma, \kappa, \varphi)$, the dual Kac algebra $\hat{\mathbf{K}} = (\hat{M}, \hat{\Gamma}, \hat{\kappa}, \hat{\varphi})$ of \mathbf{K} is canonically constructed as follows. M is assumed to be represented on the standard Hilbert space $L^2(\varphi)$. Let λ be the left regular representation of M on $L^2(\varphi)$ with respect to the convolution product in M , W the fundamental operator of \mathbf{K} , and Σ the flip on $L^2(\varphi) \otimes L^2(\varphi)$. Then $\hat{\mathbf{K}} = (\hat{M}, \hat{\Gamma}, \hat{\kappa}, \hat{\varphi})$ is defined by

$$\begin{aligned} \hat{M} &= \lambda(M), \\ \hat{\Gamma}(\lambda(f)) &= \Sigma W^* (\lambda(f) \otimes 1) W \Sigma, \quad f \in M, \\ \hat{\kappa}(\lambda(f)) &= \lambda(\kappa(f)), \quad f \in M, \\ \hat{\varphi}(\lambda(f)) &= \varphi(e f), \quad f \in M, \end{aligned}$$

where e is the unit of M with respect to the convolution product.

In the following, we shall give an example of finite dimensional Kac algebras by using Kac-Paljutkin's method. For details, see Kac and Paljutkin [5].

Let $k \in \mathbf{N}$, $k \geq 3$ be fixed and η a primitive k -th root of 1. We set

$$G = \mathbf{Z}_k \times \mathbf{Z}_k = \{(i, j) \mid i, j = 0, 1, \dots, k-1\}$$

and define $k \times k$ unitary matrices $\{p_{(i,j)}\}$, $\{u_{(i,j)}\}$ and $\{v_{(i,j)}\}$ parametrized by G by

$$p_{(i,j)} = u_{(i,j)} = \sum_{m=1}^k \eta^{im} e_{m,m+j}, \quad v_{(i,j)} = \overline{u_{(i,j)}} = \sum_{m=1}^k \eta^{-im} e_{m,m+j}.$$

Here $\{e_{ij}\}_{i,j=1}^k$ means the usual matrix units in $M_k(\mathbf{C})$. It is easy to check that the above matrices satisfy the conditions in Kac-Paljutkin [5], hence we have a $2k^2$ dimensional Kac algebra $\mathbf{K} = (M, \Gamma, \kappa, \varphi)$ whose structure is given by the following:

$$M = \bigoplus_{(i,j) \in G} \mathbf{C} e_{(i,j)} \oplus M_k(\mathbf{C}),$$

where $\{e_{(i,j)}\}_{(i,j) \in G}$ denotes the 1-dimensional central minimal projections,

$$\begin{aligned}\Gamma(e_{(i,j)}) &= \sum_{(m,n) \in G} e_{(m,n)} \otimes e_{(-m,-n)} \\ &\quad + \frac{1}{k} \sum_{m,n,s,t=1}^k (u_{(i,j)})_{m,s} \overline{(u_{(i,j)})_{n,t}} e_{mn} \otimes e_{st}, \quad (i,j) \in G, \\ \Gamma(X) &= \sum_{(i,j) \in G} e_{(-i,-j)} \otimes u_{(i,j)} X u_{(i,j)}^* \\ &\quad + \sum_{(i,j) \in G} v_{(i,j)} X v_{(i,j)}^* \otimes e_{(i,j)}, \quad X \in M_k(\mathbf{C}), \\ \kappa(e_{(i,j)}) &= e_{(-i,-j)}, \quad (i,j) \in G, \\ \kappa(X) &= {}^t X, \quad X \in M_k(\mathbf{C}),\end{aligned}$$

where ${}^t X$ means the transpose of X ,

$$\varphi \left(\sum_{(i,j) \in G} x_{(i,j)} e_{(i,j)} + (x_{ij})_{i,j=1}^k \right) = \frac{1}{2k^2} \left(\sum_{(i,j) \in G} x_{(i,j)} + k \sum_{i=1}^k x_{ii} \right).$$

3. THE DUAL KAC ALGEBRA

In this section, we shall compute the dual of the Kac algebra $\mathbf{K} = (M, \Gamma, \kappa, \varphi)$ constructed in the previous section. It is sufficient to calculate the convolution structure in M .

Let $*$ be the convolution product of M and $\#$ the involution of M , that is, they are defined by the following relations :

$$\begin{aligned}\langle a, x * y \rangle &= \langle \Gamma(a), x \otimes y \rangle \\ &= (\varphi \otimes \varphi)(\Gamma(a)(x \otimes y)), \quad x, y, a \in M, \\ x^\# &= \kappa(x^*) = \kappa(x)^*, \quad x \in M.\end{aligned}$$

Lemma 1. *Let $A = (a_{ij})$, $B = (b_{ij}) \in M_k(\mathbf{C})$. Then we have*

$$\begin{aligned}\text{(i)} \quad e_{(i,j)} * e_{(i',j')} &= \frac{1}{2k^2} e_{(i+i', j+j')}, \\ \text{(ii)} \quad e_{(i,j)} * A &= \frac{1}{2k^2} \sum_{m,n=1}^k \eta^{i(m-n)} a_{m+j, n+j} e_{mn}, \\ \text{(iii)} \quad A * e_{(i,j)} &= \frac{1}{2k^2} \sum_{m,n=1}^k \eta^{i(m-n)} a_{m-j, n-j} e_{mn}, \\ \text{(iv)} \quad A * B &= \sum_{(i,j) \in G} c_{(i,j)} e_{(i,j)},\end{aligned}$$

where

$$c_{(i,j)} = \frac{1}{2k} \sum_{m,n=1}^k \eta^{-i(m-n)} a_{m,n} b_{m+j, n+j}.$$

Hence, for $X = \sum_{(i,j) \in G} x_{(i,j)} e_{(i,j)} + (x_{ij})_{i,j=1}^k$ and $Y = \sum_{(i,j) \in G} y_{(i,j)} e_{(i,j)} + (y_{ij})_{i,j=1}^k$, we get

$$X * Y = \sum_{(i,j) \in G} z_{(i,j)} e_{(i,j)} + (z_{ij})_{i,j=1}^k,$$

where

$$z_{(i,j)} = \frac{1}{2k^2} \sum_{(m,n) \in G} x_{(i-m,j-n)} y_{(m,n)} + \frac{1}{2k} \sum_{m,n=1}^k \eta^{-i(m-n)} x_{m,n} y_{m+j,n+j},$$

$$z_{mn} = \frac{1}{2k^2} \left(\sum_{(i,j) \in G} \eta^{i(m-n)} (x_{(i,j)} y_{m+j,n+j} + y_{(i,j)} x_{m-j,n-j}) \right).$$

Proof. Let $X = \sum_{(m,n) \in G} x_{(m,n)} e_{(m,n)} + (x_{mn})_{m,n=1}^k \in M$.

(i) We compute

$$\begin{aligned} \langle X, e_{(i,j)} * e_{(i',j')} \rangle &= \langle \Gamma(X), e_{(i,j)} \otimes e_{(i',j')} \rangle \\ &= (\varphi \otimes \varphi) (\Gamma(X) (e_{(i,j)} \otimes e_{(i',j')})) \\ &= \left(\frac{1}{2k^2} \right)^2 x_{(i+i',j+j')} \\ &= \frac{1}{2k^2} \varphi (X e_{(i+i',j+j')}) \\ &= \left\langle X, \frac{1}{2k^2} e_{(i+i',j+j')} \right\rangle. \end{aligned}$$

Hence

$$e_{(i,j)} * e_{(i',j')} = \frac{1}{2k^2} e_{(i+i',j+j')}, \quad (i,j), (i',j') \in G.$$

(ii) Since

$$\begin{aligned} \langle X, e_{(i,j)} * A \rangle &= (\varphi \otimes \varphi) (\Gamma(X) (e_{(i,j)} \otimes A)) \\ &= \frac{1}{2k^2} \varphi (u_{(-i,-j)} (x_{mn}) u_{(-i,-j)}^* A) \\ &= \frac{1}{2k^2} \varphi ((x_{mn}) u_{(-i,-j)}^* A u_{(-i,-j)}) \\ &= \left\langle X, \frac{1}{2k^2} u_{(-i,-j)}^* A u_{(-i,-j)} \right\rangle \\ &= \left\langle X, \frac{1}{2k^2} u_{(i,j)} A u_{(i,j)}^* \right\rangle, \end{aligned}$$

we get

$$\begin{aligned} e_{(i,j)} * A &= \frac{1}{2k^2} u_{(i,j)} A u_{(i,j)}^* \\ &= \frac{1}{2k^2} \sum_{m,n=1}^k \eta^{i(m-n)} a_{m+j,n+j} e_{mn}. \end{aligned}$$

(iii) follows from a similar calculation.

(iv) Since

$$\begin{aligned}
 & \langle X, A * B \rangle \\
 &= (\varphi \otimes \varphi)(\Gamma(X)(A \otimes B)) \\
 &= \frac{1}{k} \sum_{(i,j) \in G} x_{(i,j)} \sum_{p,q,r,s=1}^k (p_{(i,j)})_{p,r} \overline{(p_{(i,j)})_{q,s}} (\varphi \otimes \varphi)((e_{pq} \otimes e_{rs})(A \otimes B)) \\
 &= \sum_{(i,j) \in G} \frac{1}{2k^2} x_{(i,j)} \left(\frac{1}{2k} \sum_{p,q,r,s=1}^k (p_{(i,j)})_{p,r} \overline{(p_{(i,j)})_{q,s}} a_{qp} b_{sr} \right) \\
 &= \left\langle X, \sum_{(i,j) \in G} \left(\frac{1}{2k} \sum_{p,q,r,s=1}^k (p_{(i,j)})_{p,r} \overline{(p_{(i,j)})_{q,s}} a_{qp} b_{sr} \right) e_{(i,j)} \right\rangle,
 \end{aligned}$$

we have

$$\begin{aligned}
 A * B &= \sum_{(i,j) \in G} \left(\frac{1}{2k} \sum_{p,q,r,s=1}^k (p_{(i,j)})_{p,r} \overline{(p_{(i,j)})_{q,s}} a_{qp} b_{sr} \right) e_{(i,j)} \\
 &= \sum_{(i,j) \in G} \left(\frac{1}{2k} \sum_{m,n=1}^k \eta^{-i(m-n)} a_{m,n} b_{m+j,n+j} \right) e_{(i,j)}.
 \end{aligned}$$

□

Lemma 2. Let $X = \sum_{(i,j) \in G} x_{(i,j)} e_{(i,j)} + (x_{ij})_{i,j=1}^k \in M$.

(i) $X * X$ if and only if

$$\begin{cases} x_{(i,j)} = \frac{1}{2k^2} \sum_{(m,n) \in G} x_{(i-m,j-n)} x_{(m,n)} + \frac{1}{2k} \sum_{m,n=1}^k \eta^{-i(m-n)} x_{m,n} x_{m+j,n+j}, \\ x_{m,n} = \frac{1}{2k^2} \left(\sum_{(i,j) \in G} \eta^{i(m-n)} x_{(i,j)} (x_{m+j,n+j} + x_{m-j,n-j}) \right). \end{cases}$$

(ii) $X^\# = X$ if and only if

$$\begin{cases} x_{(-i,-j)} = \overline{x_{(i,j)}}, \\ x_{ij} \in \mathbf{R}. \end{cases}$$

Proof. (i) follows from Lemma 1.

(ii) follows from the definition of the involution $\#$.

□

3.1. The case k : odd. We first compute the center of M with respect to the convolution product.

Lemma 3. Let $Z(M, *)$ denote the center of M with respect to the convolution $*$. Then we have

$$\begin{aligned}
 & Z(M, *) \\
 &= \left\{ \sum_{(i,j) \in G} x_{(i,j)} e_{(i,j)} + (x_{ij})_{i,j=1}^k \mid \begin{array}{l} x_{(i,-j)} = x_{(i,j)}, \quad i, j = 0, 1, \dots, k-1 \\ x_{i+n,j+n} = x_{i,j}, \quad i, j, n = 1, 2, \dots, k \end{array} \right\}.
 \end{aligned}$$

In particular,

$$\dim Z(M, *) = \frac{k(k+3)}{2}.$$

Proof. Let $X = \sum_{(i,j) \in G} x_{(i,j)} e_{(i,j)} + (x_{ij})_{i,j=1}^k \in Z(M, *)$. Let $(m, n) \in G$ be fixed.

Then the equation $e_{(m,n)} * X = X * e_{(m,n)}$ implies

$$x_{i+n, j+n} = x_{i,j}, \quad i, j, n = 1, 2, \dots, k.$$

Moreover, since $A * X = X * A$ for any $A \in M_k(\mathbf{C})$, we obtain

$$x_{(i,-j)} = x_{(i,j)}, \quad i, j = 0, 1, \dots, k-1.$$

□

Lemma 4. Let $l \in \{0, 1, \dots, k-1\}$. If we set

$$p_{l,+} = \sum_{(i,j) \in G} \eta^{il} e_{(i,j)} + \sum_{m=1}^k e_{m,m+l}$$

and

$$p_{l,-} = \sum_{(i,j) \in G} \eta^{il} e_{(i,j)} - \sum_{m=1}^k e_{m,m+l},$$

then $p_{l,\pm}$'s are 1-dimensional central projections.

Proof. The assertion follows from a direct computation. □

Lemma 5. Let $u \in \{0, 1, \dots, k-1\}$ and $v \in \{1, 2, \dots, \frac{k-1}{2}\}$. Put

$$p_{u,v} = 2 \sum_{(i,j) \in G} (\eta^{iu+jv} + \eta^{iu-jv}) e_{(i,j)}.$$

Then $p_{u,v}$'s are 2-dimensional central minimal projections. Furthermore, a system of matrix units $\{e_{s,t}^{u,v}\}_{s,t=1}^2$ in $M * p_{u,v} \cong M_2(\mathbf{C})$ is given by

$$\begin{aligned} e_{1,1}^{u,v} &= 2 \sum_{(i,j) \in G} \eta^{iu+jv} e_{(i,j)}, \\ e_{1,2}^{u,v} &= 2 \sum_{m=1}^k \eta^{-mv} e_{m,m+u}, \\ e_{2,1}^{u,v} &= 2 \sum_{m=1}^k \eta^{mv} e_{m,m+u}, \\ e_{2,2}^{u,v} &= 2 \sum_{(i,j) \in G} \eta^{iu-jv} e_{(i,j)}. \end{aligned}$$

Proof. Direct computations. □

Summing up the calculations, we have

Theorem 6. The algebraic structure of \hat{M} is given by

$$\hat{M} = \underbrace{\mathbf{C} \oplus \mathbf{C} \oplus \dots \oplus \mathbf{C}}_{2k} \oplus \underbrace{M_2(\mathbf{C}) \oplus M_2(\mathbf{C}) \oplus \dots \oplus M_2(\mathbf{C})}_{\frac{k(k-1)}{2}}.$$

3.2. The case k : even.

Lemma 7. *The center $Z(M, *)$ of M with respect to $*$ is given by*

$$Z(M, *) = \left\{ \sum_{(i,j) \in G} x_{(i,j)} e_{(i,j)} + (x_{ij})_{i,j=1}^k \left| \begin{array}{l} x_{(i,-j)} = x_{(i,j)}, \quad i, j = 0, 1, \dots, k-1 \\ x_{i+2n, j+2n} = x_{i,j}, \quad i, j, n = 1, 2, \dots, k \end{array} \right. \right\}.$$

In particular,

$$\dim Z(M, *) = \frac{k(k+6)}{2}.$$

Proof. Let $X = \sum_{(i,j) \in G} x_{(i,j)} e_{(i,j)} + (x_{ij})_{i,j=1}^k \in Z(M, *)$. Then the equality $e_{(m,n)} * X = X * e_{(m,n)}$ for $(m, n) \in G$ implies

$$x_{i+2n, j+2n} = x_{i,j}, \quad i, j, n = 1, 2, \dots, k.$$

Since $A * X = X * A$ for $A \in M_k(\mathbf{C})$, we have

$$x_{(i,-j)} = x_{(i,j)}, \quad i, j = 0, 1, \dots, k-1.$$

□

Lemma 8. *Let $l \in \{0, 1, \dots, k-1\}$. We set*

$$\begin{aligned} p_{l,1} &= \sum_{(i,j) \in G} \eta^{il} e_{(i,j)} + \sum_{m=1}^k e_{m, m+l}, \\ p_{l,2} &= \sum_{(i,j) \in G} \eta^{il} e_{(i,j)} - \sum_{m=1}^k e_{m, m+l}, \\ p_{l,3} &= \sum_{(i,j) \in G} (-1)^j \eta^{il} e_{(i,j)} + \sum_{m=1}^k (-1)^m e_{m, m+l}, \\ p_{l,4} &= \sum_{(i,j) \in G} (-1)^j \eta^{il} e_{(i,j)} - \sum_{m=1}^k (-1)^m e_{m, m+l}. \end{aligned}$$

Then $p_{l,i}$'s are 1-dimensional central projections.

Proof. The result follows from a straightforward calculation. □

Lemma 9. *Let $u \in \{0, 1, \dots, k-1\}$ and $v \in \{1, 2, \dots, \frac{k}{2}-1\}$. Set*

$$p_{u,v} = 2 \sum_{(i,j) \in G} (\eta^{iu+jv} + \eta^{iu-jv}) e_{(i,j)}.$$

Then it follows that $p_{u,v}$'s are 2-dimensional central minimal projections. Furthermore, a system of matrix units $\{e_{s,t}^{u,v}\}_{s,t=1}^2$ in $M * p_{u,v}$ is given by

$$\begin{aligned} e_{1,1}^{u,v} &= 2 \sum_{(i,j) \in G} \eta^{iu+jv} e_{(i,j)}, \\ e_{1,2}^{u,v} &= 2 \sum_{m=1}^k \eta^{-mv} e_{m,m+u}, \\ e_{2,1}^{u,v} &= 2 \sum_{m=1}^k \eta^{mv} e_{m,m+u}, \\ e_{2,2}^{u,v} &= 2 \sum_{(i,j) \in G} \eta^{iu-jv} e_{(i,j)}. \end{aligned}$$

Proof. The assertions follow from a direct computation. \square

Theorem 10. *The algebraic structure of \hat{M} is given by*

$$\hat{M} = \underbrace{\mathbf{C} \oplus \mathbf{C} \oplus \cdots \oplus \mathbf{C}}_{4k} \oplus \underbrace{M_2(\mathbf{C}) \oplus M_2(\mathbf{C}) \oplus \cdots \oplus M_2(\mathbf{C})}_{\frac{k(k-2)}{2}}.$$

Remark 11. We can compute the paragroup structure of the inclusion associated with the Kac algebra $\mathbf{K} = (M, \Gamma, \kappa, \varphi)$. (See Ocneanu [12].)

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