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# Twisting and Rieffel's deformation of locally compact quantum groups. Deformation of the Haar measure.

Pierre Fima\* and Leonid Vainerman†

## Abstract

We develop the twisting construction for locally compact quantum groups. A new feature, in contrast to the previous work of M. Enock and the second author, is a non-trivial deformation of the Haar measure. Then we construct Rieffel's deformation of locally compact quantum groups and show that it is dual to the twisting. This allows to give new interesting concrete examples of locally compact quantum groups, in particular, deformations of the classical  $az + b$  group and of the Woronowicz' quantum  $az + b$  group.

## 1 Introduction

The problem of extension of harmonic analysis on abelian locally compact (l.c.) groups, to non abelian ones, leads to the introduction of more general objects. Indeed, the set  $\hat{G}$  of characters of an abelian l.c. group  $G$  is again an abelian l.c. group - the dual group of  $G$ . The Fourier transform maps functions on  $G$  to functions on  $\hat{G}$ , and the Pontrjagin duality theorem claims that  $\hat{\hat{G}}$  is isomorphic to  $G$ . If  $G$  is not abelian, the set of its characters is too small, and one should use instead the set  $\hat{G}$  of (classes of) its unitary irreducible representations and their matrix coefficients. For compact groups, this leads to the Peter-Weyl theory and to the Tannaka-Krein duality, where  $\hat{G}$  is not a group, but allows to reconstruct  $G$ . Such a non-symmetric duality was established for unimodular groups by W.F. Stinespring, and for general l.c. groups by P. Eymard and T. Tatsuuma.

In order to restore the symmetry of the duality, G.I. Kac introduced in 1961 a category of *ring groups* which contained unimodular groups and their duals. The duality constructed by Kac extended those of Pontrjagin, Tannaka-Krein and Stinespring. This theory was completed in early 70-s by G.I. Kac and the second author, and independently by M. Enock and J.-M. Schwartz, in order

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to cover all l.c. groups. The objects of this category are called *Kac algebras* [2]. L.c. groups and their duals can be viewed respectively as commutative and co-commutative Kac algebras, the corresponding duality covered all known versions of duality for l.c. groups.

Quantum groups discovered by V.G. Drinfeld and others gave new important examples of Hopf algebras obtained by deformation of universal enveloping algebras and of function algebras on Lie groups. Their operator algebraic versions did not verify some of Kac algebra axioms and motivated strong efforts to construct a more general theory. Important steps in this direction were made by S.L. Woronowicz with his theory of compact quantum groups and a series of important concrete examples, S. Baaq and G. Skandalis with their fundamental concept of a multiplicative unitary and A. Van Daele who introduced an important notion of a multiplier Hopf algebra. Finally, the theory of l.c. quantum groups was proposed by J. Kustermans and S. Vaes [8], [9].

A number of "isolated" examples of non-trivial (i.e., non commutative and non cocommutative) l.c. quantum groups was constructed by S.L. Woronowicz and other people. They were formulated in terms of generators of certain Hopf  $\ast$ -algebras and commutation relations between them. It was much harder to represent them by operators acting on a Hilbert space, to associate with them an operator algebra and to construct all ingredients of a l.c. quantum group. There was no general approach to these highly nontrivial problems, and one must design specific methods in each specific case (see, for example, [19], [17]).

In [3], [16] M. Enock and the second author proposed a systematic approach to the construction of non-trivial Kac algebras by twisting. To illustrate it, consider a cocommutative Kac algebra structure on the group von Neumann algebra  $M = \mathcal{L}(G)$  of a non commutative l.c. group  $G$  with comultiplication  $\Delta(\lambda_g) = \lambda_g \otimes \lambda_g$  ( $\lambda_g$  is the left translation by  $g \in G$ ). Let us construct on  $M$  another (in general, non cocommutative) Kac algebra structure with comultiplication  $\Delta_\Omega(\cdot) = \Omega\Delta(\cdot)\Omega^*$ , where  $\Omega \in M \otimes M$  is a unitary verifying certain 2-cocycle condition. In order to find such an  $\Omega$ , let us, following to M. Rieffel [11] and M. Landstad [10], take an inclusion  $\alpha : L^\infty(\hat{K}) \rightarrow M$ , where  $\hat{K}$  is the dual to some abelian subgroup  $K$  of  $G$  such that  $\delta|_K = 1$  ( $\delta(\cdot)$  is the module of  $G$ ). Then, one lifts a usual 2-cocycle  $\Psi$  of  $\hat{K} : \Omega = (\alpha \otimes \alpha)\Psi$ . The main result of [3] is that Haar measure on  $\mathcal{L}(G)$  gives also the Haar measure of the deformed object.

Even though a series of non-trivial Kac algebras was constructed in this way, the above mentioned "unimodularity" condition on  $K$  was restrictive. Here we develop the twisting construction for l.c. quantum groups without this condition and compute explicitly the deformed Haar measure. Thus, we are able to construct l.c. quantum groups which are not Kac algebras and to deform objects which are already non-trivial, for example, the  $az + b$  quantum group [19], [17].

A dual construction that we call Rieffel's deformation of a l.c. group has been proposed in [11], [12], and [10], where, using a bicharacter on an abelian subgroup, one deforms the algebra of functions on a group. This construction has been recently developed by Kasprzak [6] who showed that the dual comul-

tiplication is exactly the twisted comultiplication of  $\mathcal{L}(G)$ . Unfortunately, a trace that he constructed on the deformed algebra is invariant only under the above mentioned "unimodularity" condition. In this paper we construct Rieffel's deformation of l.c. quantum groups without this condition and compute the corresponding left invariant weight. This proves, in particular, the existence of invariant weights on the classical Rieffel's deformation. We also establish the duality between twisting and the Rieffel's deformation.

The structure of the paper is as follows. First, we recall some preliminary definitions and give our main results. In Section 3 we develop the twisting construction for l.c. quantum groups. Section 4 is devoted to the Rieffel's deformations of l.c. quantum groups and to the proof of the duality theorem. In Section 5 we present examples obtained by the two constructions: 1) from group von Neumann algebras  $\mathcal{L}(G)$ , in particular, when  $G$  is the  $az + b$  group; 2) from the  $az + b$  quantum group. Some useful technical results are collected in Appendix.

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## 2 Preliminaries and main results

### 2.1 Notations.

Let us denote by  $B(H)$  the algebra of all bounded linear operators on a Hilbert space  $H$ , by  $\otimes$  the tensor product of Hilbert spaces or von Neumann algebras and by  $\Sigma$  (resp.,  $\sigma$ ) the flip map on it. If  $H, K$  and  $L$  are Hilbert spaces and  $X \in B(H \otimes L)$  (resp.,  $X \in B(H \otimes K), X \in B(K \otimes L)$ ), we denote by  $X_{13}$  (resp.,  $X_{12}, X_{23}$ ) the operator  $(1 \otimes \Sigma^*)(X \otimes 1)(1 \otimes \Sigma)$  (resp.,  $X \otimes 1, 1 \otimes X$ ) defined on  $H \otimes K \otimes L$ . The identity map will be denoted by  $\iota$ .

Given a *normal semi-finite faithful* (n.s.f.) weight  $\theta$  on a von Neumann algebra  $M$ , we denote:  $\mathcal{M}_\theta^+ = \{x \in M^+ \mid \theta(x) < +\infty\}$ ,  $\mathcal{N}_\theta = \{x \in M \mid x^*x \in \mathcal{M}_\theta^+\}$ , and  $\mathcal{M}_\theta = \text{span } \mathcal{M}_\theta^+$ . All l.c. groups considered in this paper are supposed to be second countable, all Hilbert spaces separable and all von Neumann algebras with separable predual.

### 2.2 Locally compact quantum groups [8], [9]

A pair  $(M, \Delta)$  is called a (von Neumann algebraic) l.c. quantum group when

- $M$  is a von Neumann algebra and  $\Delta : M \rightarrow M \otimes M$  is a normal and unital \*-homomorphism which is coassociative:  $(\Delta \otimes \iota)\Delta = (\iota \otimes \Delta)\Delta$
- There exist n.s.f. weights  $\varphi$  and  $\psi$  on  $M$  such that
  - $\varphi$  is left invariant in the sense that  $\varphi((\omega \otimes \iota)\Delta(x)) = \varphi(x)\omega(1)$  for all  $x \in \mathcal{M}_\varphi^+$  and  $\omega \in M_*^+$ ,

- $\psi$  is right invariant in the sense that  $\psi((\iota \otimes \omega)\Delta(x)) = \psi(x)\omega(1)$  for all  $x \in \mathcal{M}_\psi^+$  and  $\omega \in M_*^+$ .

Left and right invariant weights are unique up to a positive scalar.

Represent  $M$  on the G.N.S. Hilbert space  $H$  of  $\varphi$  and define a unitary  $W$  on  $H \otimes H$ :

$$W^*(\Lambda(a) \otimes \Lambda(b)) = (\Lambda \otimes \Lambda)(\Delta(b)(a \otimes 1)) \quad \text{for all } a, b \in N_\varphi.$$

Here,  $\Lambda$  denotes the canonical G.N.S.-map for  $\varphi$ ,  $\Lambda \otimes \Lambda$  the similar map for  $\varphi \otimes \varphi$ . One proves that  $W$  satisfies the *pentagonal equation*:  $W_{12}W_{13}W_{23} = W_{23}W_{12}$ , and we say that  $W$  is a *multiplicative unitary*. The von Neumann algebra  $M$  and the comultiplication on it can be given in terms of  $W$  respectively as

$$M = \{(\iota \otimes \omega)(W) \mid \omega \in B(H)_*\}^{-\sigma\text{-strong}^*}$$

and  $\Delta(x) = W^*(1 \otimes x)W$ , for all  $x \in M$ . Next, the l.c. quantum group  $(M, \Delta)$  has an antipode  $S$ , which is the unique  $\sigma$ -strongly\* closed linear map from  $M$  to  $M$  satisfying  $(\iota \otimes \omega)(W) \in \mathcal{D}(S)$  for all  $\omega \in B(H)_*$  and  $S(\iota \otimes \omega)(W) = (\iota \otimes \omega)(W^*)$  and such that the elements  $(\iota \otimes \omega)(W)$  form a  $\sigma$ -strong\* core for  $S$ .  $S$  has a polar decomposition  $S = R\tau_{-i/2}$ , where  $R$  is an anti-automorphism of  $M$  and  $\tau_t$  is a one-parameter group of automorphisms of  $M$ . We call  $R$  the unitary antipode and  $\tau_t$  the scaling group of  $(M, \Delta)$ . We have  $\sigma(R \otimes R)\Delta = \Delta R$ , so  $\varphi R$  is a right invariant weight on  $(M, \Delta)$ , and we take  $\psi := \varphi R$ .

There exist a unique number  $\nu > 0$  and a unique positif self-adjoint operator  $\delta_M$  affiliated to  $M$ , such that  $[D\psi : D\varphi]_t = \nu^{\frac{it}{2}} \delta_M^{it}$ .  $\nu$  is the scaling constant of  $(M, \Delta)$  and  $\delta_M$  is the modular element of  $(M, \Delta)$ . The scaling constant can be characterized as well by the relative invariance property  $\varphi \tau_t = \nu^{-t} \varphi$ .

For the dual l.c. quantum group  $(\hat{M}, \hat{\Delta})$  we have

$$\hat{M} = \{(\omega \otimes \iota)(W) \mid \omega \in B(H)_*\}^{-\sigma\text{-strong}^*}$$

and  $\hat{\Delta}(x) = \Sigma W(x \otimes 1)W^* \Sigma$  for all  $x \in \hat{M}$ . Turn the predual  $M_*$  into a Banach algebra with the product  $\omega \mu = (\omega \otimes \mu)\Delta$  and define

$$\lambda : M_* \rightarrow \hat{M} : \lambda(\omega) = (\omega \otimes \iota)(W),$$

then  $\lambda$  is a homomorphism and  $\lambda(M_*)$  is a  $\sigma$ -strongly\* dense subalgebra of  $\hat{M}$ . A left invariant n.s.f. weight  $\hat{\varphi}$  on  $\hat{M}$  can be constructed explicitly. Let  $\mathcal{I} = \{\omega \in M_* \mid \exists C \geq 0, |\omega(x^*)| \leq C \|\Lambda(x)\| \forall x \in \mathcal{N}_\varphi\}$ . Then  $(H, \iota, \hat{\Lambda})$  is the G.N.S. construction for  $\hat{\varphi}$  where  $\lambda(\mathcal{I})$  is a  $\sigma$ -strong\*-norm core for  $\hat{\Lambda}$  and  $\hat{\Lambda}(\lambda(\omega))$  is the unique vector  $\xi(\omega)$  in  $H$  such that

$$\langle \xi(\omega), \Lambda(x) \rangle = \omega(x^*).$$

The multiplicative unitary of  $(\hat{M}, \hat{\Delta})$  is  $\hat{W} = \Sigma W^* \Sigma$ .

Since  $(\hat{M}, \hat{\Delta})$  is again a l.c. quantum group, denote its antipode by  $\hat{S}$ , its unitary antipode by  $\hat{R}$  and its scaling group by  $\hat{\tau}_t$ . Then we can construct

the dual of  $(\hat{M}, \hat{\Delta})$ , starting from the left invariant weight  $\hat{\varphi}$ . The bidual l.c. quantum group  $(\hat{\hat{M}}, \hat{\hat{\Delta}})$  is isomorphic to  $(M, \Delta)$ . Denote by  $\hat{\sigma}_t$  the modular automorphism group of the weight  $\hat{\varphi}$ . The modular conjugations of the weights  $\varphi$  and  $\hat{\varphi}$  will be denoted by  $J$  and  $\hat{J}$  respectively. Let us mention that  $R(x) = \hat{J}x^*\hat{J}$ , for all  $x \in M$ , and  $\hat{R}(y) = Jy^*J$ , for all  $y \in \hat{M}$ .

$(M, \Delta)$  is a *Kac algebra* (see [2]) if and only if  $\tau_t = \iota$  and  $\delta_M$  is affiliated to the center of  $M$ . In particular,  $(M, \Delta)$  is a Kac algebra if  $M$  is commutative. Then  $(M, \Delta)$  is generated by a usual l.c. group  $G : M = L^\infty(G)$ ,  $(\Delta_G f)(g, h) = f(gh)$ ,  $(S_G f)(g) = f(g^{-1})$ ,  $\varphi_G(f) = \int f(g) dg$ , where  $f \in L^\infty(G)$ ,  $g, h \in G$  and we integrate with respect to the left Haar measure  $dg$  on  $G$ . Then  $\psi_G$  is given by  $\psi_G(f) = \int f(g^{-1}) dg$  and  $\delta_M$  by the strictly positive function  $g \mapsto \delta_G(g)^{-1}$ .

$L^\infty(G)$  acts on  $H = L^2(G)$  by multiplication and  $(W_G \xi)(g, h) = \xi(g, g^{-1}h)$ , for all  $\xi \in H \otimes H = L^2(G \times G)$ . Then  $\hat{M} = \mathcal{L}(G)$  is the group von Neumann algebra generated by the left translations  $(\lambda_g)_{g \in G}$  of  $G$  and  $\hat{\Delta}_G(\lambda_g) = \lambda_g \otimes \lambda_g$ . Clearly,  $\hat{\Delta}_G^{op} := \sigma \circ \hat{\Delta}_G = \hat{\Delta}_G$ , so  $\hat{\Delta}_G$  is cocommutative. Every cocommutative l.c. quantum group is obtained in this way.

### 2.3 $q$ -commuting pair of operators [18]

We will use the following notion of commutation relations between unbounded operators. Let  $(T, S)$  be a pair of closed operators acting on a Hilbert space  $H$ . Suppose that  $\text{Ker}(T) = \text{Ker}(S) = \{0\}$  and denote by  $S = \text{Ph}(S)|S|$  and  $T = \text{Ph}(T)|T|$  the polar decompositions. Let  $q > 0$ . We say that  $(T, S)$  is a  *$q$ -commuting pair* and we denote it by  $TS = ST$ ,  $TS^* = q^2 S^*T$  if the following conditions are satisfied

1.  $\text{Ph}(T)\text{Ph}(S) = \text{Ph}(S)\text{Ph}(T)$  and  $|T|$  and  $|S|$  strongly commute.
2.  $\text{Ph}(T)|S|\text{Ph}(T)^* = q|S|$  and  $\text{Ph}(S)|T|\text{Ph}(S)^* = q|T|$ .

If  $T$  and  $S$  are  $q$ -commuting and normal operators then the product  $TS$  is closable and its closure, always denoted by  $TS$  has the following polar decomposition  $\text{Ph}(TS) = \text{Ph}(T)\text{Ph}(S)$  and  $|TS| = q^{-1}|T||S|$ .

### 2.4 The quantum $az + b$ group [19], [17]

Let us describe an explicit example of l.c. quantum group. Let  $s$  and  $m$  be two operators defined on the canonical basis  $(e_k)_{k \in \mathbb{Z}}$  of  $l^2(\mathbb{Z})$  by  $se_k = e_{k+1}$  and  $me_k = q^k e_k$  ( $0 < q < 1$ ). The G.N.S. space of the quantum  $az + b$  group is  $H = l^2(\mathbb{Z}^4)$ , where we define the operators

$$a = m \otimes s^* \otimes 1 \otimes s \quad \text{and} \quad b = s \otimes m \otimes s \otimes 1$$

with polar decompositions  $a = u|a|$  and  $b = v|b|$  given by

$$\begin{aligned} |a| &= m \otimes 1 \otimes 1 \otimes 1 & \text{and} & \quad u = 1 \otimes s^* \otimes 1 \otimes s \\ |b| &= 1 \otimes m \otimes 1 \otimes 1 & \text{and} & \quad v = s \otimes 1 \otimes s \otimes 1. \end{aligned}$$

Then  $u|b| = q|b|u$ ,  $|a|v = qv|a|$ , this is the meaning of the relations  $ab = q^2ba$  and  $ab^* = b^*a$ . Also  $\text{Sp}(|a|) = \text{Sp}(|b|) = \text{Sp}(m) = q^{\mathbb{Z}} \cup \{0\}$ ,  $\text{Sp}(u) = \text{Sp}(v) = \mathbb{S}^1$ , where  $\text{Sp}$  means the spectrum. Thus,  $\text{Sp}(a) = \text{Sp}(b) = \mathbb{C}^q \cup \{0\}$ , where  $\mathbb{C}^q = \{z \in \mathbb{C}, |z| \in q^{\mathbb{Z}}\}$ . The von Neumann algebra of the quantum  $az + b$  group is

$$M := \left\{ \text{finite sums } \sum_{k,l} f_{k,l}(|a|, |b|) v^k u^l \quad \text{for } f_{k,l} \in L^\infty(q^{\mathbb{Z}} \times q^{\mathbb{Z}}) \right\}''.$$

Consider the following version of the quantum exponential function on  $\mathbb{C}^q$ :

$$F_q(z) = \prod_{k=0}^{+\infty} \frac{1 + q^{2k}\bar{z}}{1 + q^{2k}z}.$$

The fundamental unitary of the  $az + b$  quantum group is  $W = \Sigma V^*$  where

$$V = F_q(\hat{b} \otimes b) \chi(\hat{a} \otimes 1, 1 \otimes a),$$

and  $\chi(q^{k+i\varphi}, q^{l+i\psi}) = q^{i(l\varphi+k\psi)}$  is a bicharacter on  $\mathbb{C}^q$ . The comultiplication is then given on generators by

$$W^*(1 \otimes a)W = a \otimes a \quad \text{and} \quad W^*(1 \otimes b)W^* = a \otimes b \dot{+} b \otimes 1,$$

where  $\dot{+}$  means the closure of the sum. The left invariant weight is

$$\varphi(x) = \sum_{i,j} q^{2(j-i)} f_{0,0}(q^i, q^j), \quad \text{where } x = \sum_{k,l} f_{k,l}(|a|, |b|) v^k u^l.$$

The G.N.S. construction for  $\varphi$  is given by  $(H, \iota, \Lambda)$ , where

$$\Lambda(x) = \sum_{k,l} q^{k+l} \xi_{k,l} \otimes e_k \otimes e_l \quad \text{with} \quad \xi_{k,l}(i, j) = q^{j-i} f_{k,l}(q^i, q^j).$$

The ingredients of the modular theory of  $\varphi$  are

$$\begin{aligned} J(e_r \otimes e_s \otimes e_k \otimes e_l) &= e_{r-k} \otimes e_{s+l} \otimes e_{-k} \otimes e_{-l}, \\ \nabla &= 1 \otimes 1 \otimes m^{-2} \otimes m^{-2}, \end{aligned}$$

so  $\sigma_t(a) = q^{-2it}a$  and  $\sigma'_t(b) = b$ , and the modular element is  $\delta = |a|^2$ .

The dual von Neumann algebra is

$$\widehat{M} := \left\{ \text{finite sums } \sum_{k,l} f_{k,l}(|\hat{a}|, |\hat{b}|) \hat{v}^k \hat{u}^l \quad \text{for } f_{k,l} \in L^\infty(q^{\mathbb{Z}} \times q^{\mathbb{Z}}) \right\}''.$$

Here  $\hat{a} = \hat{u}|\hat{a}|$  and  $\hat{b} = \hat{v}|\hat{b}|$  are the polar decompositions of the operators

$$\hat{a} = s^* \otimes 1 \otimes 1 \otimes m, \quad \hat{b} = s^* m \otimes (-m^{-1} \otimes m^{-1} s^* + m^{-1} s^* \otimes s^*) \otimes s.$$

The formulas for the dual comultiplication and the dual left invariant weight are the same, but this time in terms of  $\hat{a}$  and  $\hat{b}$ .

## 2.5 One-parameter groups of automorphisms of von Neumann algebras

Consider a von Neumann algebra  $M \subset \mathcal{B}(H)$  and a continuous group homomorphism  $\sigma : \mathbb{R} \rightarrow \text{Aut}(M)$ ,  $t \mapsto \sigma_t$ . There is a standard way to construct, for every  $z \in \mathbb{C}$ , a strongly closed densely defined linear multiplicative in  $z$  operator  $\sigma_z$  in  $M$ . Let  $\mathcal{S}(z)$  be the strip  $\{y \in \mathbb{C} \mid \text{Im}(y) \in [0, \text{Im}(z)]\}$ . Then we define :

- The domain  $D(\sigma_z)$  is the set of such elements  $x$  in  $M$  that the map  $t \mapsto \sigma_t(x)$  has a strongly continuous extension to  $\mathcal{S}(z)$  analytic on  $\mathcal{S}(z)^0$ .
- Consider  $x$  in  $D(\sigma_z)$  and  $f$  the unique extension of the map  $t \mapsto \sigma_t(x)$  strongly continuous on  $\mathcal{S}(z)$  and analytic on  $\mathcal{S}(z)^0$ . Then, by definition,  $\sigma_z(x) = f(z)$ .

If  $x$  is not in  $D(\sigma_z)$ , we define an unbounded operator  $\sigma_z(x)$  on  $H$  as follows:

- The domain  $D(\sigma_z(x))$  is the set of such  $\xi \in H$  that the map  $t \mapsto \sigma_t(x)\xi$  has a continuous and bounded extension to  $\mathcal{S}(z)$  analytic on  $\mathcal{S}(z)^0$ .
- Consider  $\xi$  in  $D(\sigma_z(x))$  and  $f$  the unique extension of the map  $t \mapsto \sigma_t(x)\xi$  continuous and bounded on  $\mathcal{S}(z)$ , and analytic on  $\mathcal{S}(z)^0$ . Then, by definition,  $\sigma_z(x)\xi = f(z)$ .

Let  $x$  in  $M$ , then it is easily seen that the following element is analytic

$$x(n) := \sqrt{\frac{n}{\pi}} \int_{-\infty}^{+\infty} e^{-nt^2} \sigma_t(x) dt.$$

The following lemma is a standard exercise:

- Lemma 1**
1.  $x(n) \rightarrow x$   $\sigma$ -strongly- $*$  and if  $\xi \in \mathcal{D}(\sigma_z(x))$  we have  $\sigma_z(x(n))\xi \rightarrow \sigma_z(x)\xi$ .
  2. Let  $X \subset M$  be a strongly- $*$  dense subspace of  $M$  then the set  $\{x(n), n \in \mathbb{N}, x \in X\}$  is a  $\sigma$ -strong- $*$  core for  $\sigma_z$ .

**Proposition 1** Let  $A$  be a positive self-adjoint operator affiliated with  $M$  and  $u$  a unitary in  $M$  commuting with  $A$  such that  $\sigma_t(u) = uA^{it}$  for all  $t \in \mathbb{R}$ , then  $\sigma_{-\frac{i}{2}}(u)$  is a normal operator affiliated with  $M$  and its polar decomposition is  $\sigma_{-\frac{i}{2}}(u) = uA^{\frac{1}{2}}$ .

**Proof.** Let  $\alpha \in \mathbb{R}$  and  $\mathcal{D}_\alpha$  the horizontal strip bounded by  $\mathbb{R}$  and  $\mathbb{R} - i\alpha$ . Let  $\xi \in \mathcal{D}(A^{\frac{1}{2}})$ . There exists a continuous bounded extension  $F$  of  $t \mapsto A^{it}\xi$  on  $\mathcal{D}_{\frac{1}{2}}$  analytic on  $\mathcal{D}_{\frac{1}{2}}^0$  (see Lemma 2.3 in [13]). Define  $G(z) = uF(z)$ . Then  $G(z)$  is continuous and bounded on  $\mathcal{S}(-\frac{i}{2}) = \mathcal{D}_{\frac{1}{2}}$ , and analytic on  $\mathcal{S}(-\frac{i}{2})^0$ . Moreover,  $G(t) = uF(t) = uA^{it}\xi = \sigma_t(u)\xi$ , so  $\xi \in \mathcal{D}(\sigma_{-\frac{i}{2}}(u))$  and  $\sigma_{-\frac{i}{2}}(u)\xi = G(-\frac{i}{2}) = uA^{\frac{1}{2}}\xi$ . Then  $uA^{\frac{1}{2}} \subset \sigma_{-\frac{i}{2}}(u)$ . The other inclusion is proved in the same way. ■

## 2.6 The Vaes' weight

Let  $M \subset \mathcal{B}(H)$  be a von Neumann algebra with a n.s.f. weight  $\varphi$  such that  $(H, \iota, \Lambda)$  is the G.N.S. construction for  $\varphi$ . Let  $\nabla, \sigma_t$  and  $J$  be the objects of the modular theory for  $\varphi$ , and  $\delta$  a positive self-adjoint operator affiliated with  $M$  verifying  $\sigma_t(\delta^{is}) = \lambda^{ist}\delta^{is}$ , for all  $s, t \in \mathbb{R}$  and some  $\lambda > 0$ .

**Lemma 2** [14] *There exists a sequence of self-adjoint elements  $e_n \in M$ , analytic w.r.t.  $\sigma$  and commuting with any operator that commutes with  $\delta$ , and such that, for all  $x, z \in \mathbb{C}$ ,  $\delta^x \sigma_z(e_n)$  is bounded with domain  $H$ , analytic w.r.t.  $\sigma$  and satisfying  $\sigma_t(\delta^x \sigma_z(e_n)) = \delta^x \sigma_{t+z}(e_n)$ , and  $\sigma_z(e_n)$  is a bounded sequence which converges  $*$ -strongly to 1, for all  $z \in \mathbb{C}$ . Moreover, the function  $(x, z) \mapsto \delta^x \sigma_z(e_n)$  is analytic from  $\mathbb{C}^2$  to  $M$ .*

Let  $N = \left\{ a \in M, a\delta^{\frac{1}{2}} \text{ is bounded and } \overline{a\delta^{\frac{1}{2}}} \in \mathcal{N}_\varphi \right\}$ . This is an ideal  $\sigma$ -strongly\* dense in  $M$  and the map  $a \mapsto \Lambda(\overline{a\delta^{\frac{1}{2}}})$  is  $\sigma$ -strong\*-norm closable; its closure will be denoted by  $\Lambda_\delta$ .

**Proposition 2** [14] *There exists a unique n.s.f. weight  $\varphi_\delta$  on  $M$  such that  $(H, \iota, \Lambda_\delta)$  is a G.N.S. construction for  $\varphi_\delta$ . Moreover,*

- *the objects of the modular theory of  $\varphi_\delta$  are  $J_\delta = \lambda^{\frac{1}{4}}J$  and  $\nabla_\delta = J\delta^{-1}J\delta\nabla$ ,*
- *$[D\varphi_\delta : D\varphi]_t = \lambda^{i\frac{t}{2}}\delta^{it}$ .*

## 2.7 Main results

Let  $(M, \Delta)$  be a l.c. quantum group with left and right invariant weights  $\varphi$  and  $\psi = \varphi \circ R$ , and the corresponding modular groups  $\sigma$  and  $\sigma'$ . Let  $\Omega \in M \otimes M$  be a 2-cocycle, i.e., a unitary such that  $(\Omega \otimes 1)(\Delta \otimes \iota)(\Omega) = (1 \otimes \Omega)(\iota \otimes \Delta)(\Omega)$ . Then obviously  $\Delta_\Omega = \Omega\Delta(\cdot)\Omega^*$  is a comultiplication on  $M$ . If  $(M, \Delta)$  is discrete quantum group and  $\Omega$  is any 2-cocycle on  $(M, \Delta)$ , then  $(M, \Delta_\Omega)$  is again a discrete quantum group [1]. If  $(M, \Delta)$  is not discrete, it is not known, in general, if  $(M, \Delta_\Omega)$  is a l.c. quantum group. Let us consider the following special construction of  $\Omega$ . Let  $G$  be l.c. group and  $\alpha$  be a unital normal faithful  $*$ -homomorphism from  $L^\infty(G)$  to  $M$  such that  $\alpha \otimes \alpha \circ \Delta_G = \Delta \circ \alpha$ . In this case we say that  $G$  is a *co-subgroup* of  $(M, \Delta)$ , and we write  $\widehat{G} < (M, \Delta)$ . Then the von Neumann algebraic version of Proposition 5.45 in [8] gives

$$\tau_t \circ \alpha = \alpha \quad \text{and} \quad R \circ \alpha(F) = \alpha(F(\cdot^{-1})), \quad \forall F \in L^\infty(G).$$

Let  $\Psi$  be a continuous bicharacter on  $G$ . Then  $\Omega = (\alpha \otimes \alpha)(\Psi)$  is a 2-cocycle on  $(M, \Delta)$ . In [3] it was supposed that  $\sigma_t$  acts trivially on the image of  $\alpha$  and it was shown that in this case,  $\varphi$  is also  $\Delta_\Omega$ -left invariant. Here we suppose that  $\sigma_t$  acts by translations, i.e., that there exists a continuous group homomorphism  $t \mapsto \gamma_t$  from  $\mathbb{R}$  to  $G$  such that  $\sigma_t(\alpha(F)) = \alpha(F(\cdot\gamma_t^{-1}))$ . In this case we say that the co-subgroup  $G$  is *stable*. Then  $\sigma'_t$  also acts by translations:

$$\sigma'_t \circ \alpha(F) = R \circ \sigma_{-t} \circ R \circ \alpha(F) = \alpha(F(\cdot\gamma_t^{-1})) = \sigma_t \circ \alpha(F). \quad (1)$$

In particular,  $\delta^{it}\alpha(F) = \alpha(F)\delta^{it}, \forall t \in \mathbb{R}, F \in L^\infty(G)$ . In our case  $\varphi$  is not necessarily  $\Delta_\Omega$ -left invariant, and one has to construct another weight on  $M$ . Note that  $(t, s) \mapsto \Psi(\gamma_t, \gamma_s)$  is a bicharacter on  $\mathbb{R}$ . Thus, there exists  $\lambda > 0$  such that  $\Psi(\gamma_t, \gamma_s) = \lambda^{its}$  for all  $s, t \in \mathbb{R}$ . Let us define the following unitaries in  $M$ :

$$u_t = \lambda^{i\frac{t^2}{2}} \alpha(\Psi(\cdot, \gamma_t^{-1})) \quad \text{and} \quad v_t = \lambda^{i\frac{t^2}{2}} \alpha(\Psi(\gamma_t^{-1}, \cdot)).$$

Then equation (1) and the definition of a bicharacter imply that  $u_t$  is a  $\sigma$ -cocycle and  $v_t$  is a  $\sigma'$ -cocycle. The converse of the Connes' Theorem gives then n.s.f. weights  $\varphi_\Omega$  and  $\psi_\Omega$  on  $M$  such that:

$$u_t = [D\varphi_\Omega : D\varphi]_t \quad \text{and} \quad v_t = [D\psi_\Omega : D\psi]_t.$$

The main result of Section 3 is the following. We denote by  $W$  the multiplicative unitary of  $(M, \Delta)$ , and put  $W_\Omega^* = \Omega(\hat{J} \otimes J)W\tilde{\Omega}(\hat{J} \otimes J)$ .

**Theorem 1**  *$(M, \Delta_\Omega)$  is a l.c. quantum group :*

- $\varphi_\Omega$  is left invariant,
- $\psi_\Omega$  is right invariant,
- $W_\Omega$  is the fundamental multiplicative unitary.
- The scaling group and the scaling constant are  $\tau_t^\Omega = \tau_t, \nu_\Omega = \nu$ .

If  $G$  is abelian, we compute explicitly the modular element and the antipode.

In section 4 we construct the Rieffel's deformation of a l.c. quantum group with an abelian stable co-subgroup  $\hat{G} < (M, \Delta)$  and prove that this construction is dual to the twisting. Switching to the additive notations for  $G$ , define  $L_\gamma = \alpha(u_\gamma)$  and  $R_\gamma = JL_\gamma J$ , where  $\gamma \in \hat{G}$ ,  $u_\gamma = \langle \gamma, g \rangle \in L^\infty(G)$ , and  $J$  is the modular conjugation of  $\varphi$ . Then Proposition 3 shows that  $\hat{G}^2$  acts on  $\widehat{M}$  by conjugation by the unitaries  $L_{\gamma_1} R_{\gamma_2}$ . We call this action the *left-right action*. Let  $N = \widehat{G}^2 \rtimes \widehat{M}$  be the crossed product von Neumann algebra generated by  $\lambda_{\gamma_1, \gamma_2}$  and  $\pi(x)$ , where  $\gamma_i \in \hat{G}$  and  $x \in \widehat{M}$ , and let  $\theta$  be the dual action of  $G^2$  on  $N$ . We show that there exists a unique unital normal \*-homomorphism  $\Gamma$  from  $N$  to  $N \otimes N$  such that  $\Gamma(\lambda_{\gamma_1, \gamma_2}) = \lambda_{\gamma_1, 0} \otimes \lambda_{0, \gamma_2}$  and  $\Gamma(\pi(x)) = (\pi \otimes \pi)\hat{\Delta}(x)$ . Let  $\Psi$  be a continuous bicharacter on  $G$ . Note that, for all  $g \in G$ , we have  $\Psi_g \in \hat{G}$ , where  $\Psi_g(h) = \Psi(h, g)$ . We denote by  $\theta^\Psi$  the *twisted dual action* of  $G^2$  on  $N$ :

$$\theta_{(g_1, g_2)}^\Psi(x) = \lambda_{\Psi_{g_1}, \Psi_{g_2}} \theta_{(g_1, g_2)}(x) \lambda_{\Psi_{g_1}, \Psi_{g_2}}^*, \quad \text{for any } g_1, g_2 \in G, x \in \widehat{G}^2 \rtimes \widehat{M}, \quad (2)$$

and by  $N_\Omega$  the fixed point algebra under this action (we would like to point out that  $N_\Omega$  is not a deformation of  $N$ , it is just a fixed point algebra with respect to the action  $\theta^\Psi$  related to  $\Omega$ ). Put  $\Upsilon = (\lambda_R \otimes \lambda_L)(\tilde{\Psi}^*) \in N \otimes N$ , where  $\lambda_R$  and  $\lambda_L$  are the unique unital normal \*-homomorphisms from  $L^\infty(G)$  to  $N$  such that  $\lambda_L(u_\gamma) = \lambda_{\gamma, 0}$  and  $\lambda_R(u_\gamma) = \lambda_{0, \gamma}$ , and put  $\Gamma_\Omega(\cdot) = \Upsilon\Gamma(\cdot)\Upsilon^*$ . Then we show that  $\Gamma_\Omega$  is a comultiplication on  $N_\Omega$  and construct a left invariant weight

on  $(N_\Omega, \Gamma_\Omega)$ . Because  $\theta_{g_1, g_2}^\Psi(\lambda_{\gamma_1, \gamma_2}) = \theta_{g_1, g_2}(\lambda_{\gamma_1, \gamma_2}) = \overline{\langle \gamma_1, g_1 \rangle \langle \gamma_2, g_2 \rangle} \lambda_{\gamma_1, \gamma_2}$ , we have a canonical isomorphism  $N = \widehat{G}^2 \rtimes \widehat{M} \rightarrow \widehat{G}^2 \rtimes N_\Omega$  intertwining the twisted dual action on  $N$  with the dual action on  $\widehat{G}^2 \rtimes N_\Omega$ . Denoting by  $\tilde{\varphi}$  the dual weight of  $\hat{\varphi}$  on  $N$  and by  $\tilde{\sigma}$  its modular group, we show that  $w_t = \lambda^{-it^2} \lambda_R(\Psi(-\gamma_t, \cdot))$  is a  $\tilde{\sigma}$ -cocycle. This implies the existence of a unique n.s.f.  $\tilde{\mu}_\Omega$  on  $N$  such that  $w_t = [D\tilde{\mu}_\Omega : D\tilde{\varphi}]_t$ . Moreover, one can show that  $\tilde{\mu}_\Omega$  is  $\theta^\Psi$  invariant. Thus, there exists a unique n.s.f.  $\mu_\Omega$  on  $N_\Omega$  such that the dual weight of  $\mu_\Omega$  is  $\tilde{\mu}_\Omega$ . In order to formulate the main result of Section 4, let us denote by  $(\widehat{M}_\Omega, \widehat{\Delta}_\Omega)$  the dual of  $(M, \Delta_\Omega)$ .

**Theorem 2**  $(N_\Omega, \Gamma_\Omega)$  is a l.c. quantum group and  $\mu_\Omega$  is left invariant. Moreover there is a canonical isomorphism  $(N_\Omega, \Gamma_\Omega) \simeq (\widehat{M}_\Omega, \widehat{\Delta}_\Omega)$ .

Note that the Rieffel's deformation in the  $C^*$ -setting was constructed by the first author in [4], see also Remark 4 and [5] for an overview.

In Section 5 we calculate explicitly two examples. It is known that if  $H$  is an abelian closed subgroup of a l.c. group  $G$ , then there is a unique faithful unital normal  $*$ -homomorphism  $\alpha$  from  $L^\infty(\widehat{H})$  to  $\mathcal{L}(G)$  such that  $\alpha(u_h) = \lambda_G(h)$ , for all  $h \in \widehat{H}$ , where  $\lambda_G$  is the left regular representation of  $G$ , so  $H < (\mathcal{L}(G), \widehat{\Delta}_G)$  is a co-subgroup. The left (and right) invariant weight on  $\mathcal{L}(G)$  is the Plancherel weight for which  $\sigma_t(\lambda_g) = \delta_G^{it}(g)\lambda_g$ , for all  $g \in G$ , where  $\delta_G$  is the modular function of  $G$ . Then  $\sigma_t \circ \alpha(u_g) = \alpha(u_g(\cdot - \gamma_t))$ , where  $\gamma_t$  is the character on  $K$  defined by  $\langle \gamma_t, g \rangle = \delta_G^{-it}(g)$ . Because the vector space spanned by the  $u_h$  for  $h \in H$  is dense in  $L^\infty(\widehat{H})$ , we have  $\sigma_t \circ \alpha(F) = \alpha(F(\cdot - \gamma_t))$ , for all  $F \in L^\infty(\widehat{K})$ . Thus,  $H < (\mathcal{L}(G), \widehat{\Delta}_G)$  is stable. So, given a bicharacter  $\Psi$  on  $\widehat{H}$ , we can perform the twisting construction. The deformation of the Haar weight will be non trivial when  $H$  is not in the kernel of the modular function of  $G$ .

Let  $G = \mathbb{C}^* \rtimes \mathbb{C}$  be the  $az + b$  group and  $H = \mathbb{C}^*$  be the abelian closed subgroup of elements of the form  $(z, 0)$  with  $z \in \mathbb{C}^*$ . Identifying  $\widehat{\mathbb{C}^*}$  with  $\mathbb{Z} \times \mathbb{R}_+^*$ :

$$\mathbb{Z} \times \mathbb{R}_+^* \rightarrow \widehat{\mathbb{C}^*}, \quad (n, \rho) \mapsto \gamma_{n, \rho} = (re^{i\theta} \mapsto e^{i \ln r \ln \rho} e^{in\theta}),$$

let us define, for all  $x \in \mathbb{R}$ , the following bicharacter on  $\mathbb{Z} \times \mathbb{R}_+^*$ :

$$\Psi_x((n, \rho), (k, r)) = e^{ix(k \ln \rho - n \ln r)}$$

and perform the twisting construction. We obtain a family of l.c. quantum groups  $(M_x, \Delta_x)$  with trivial scaling group and scaling constant. Moreover, we show that the antipode is not deformed. The main result of Section 5.1 is the following. Let us denote by  $\varphi$  the Plancherel weight on  $\mathcal{L}(G)$  and by a subscript  $x$  the objects associated with  $(M_x, \Delta_x)$ .

**Theorem 3** We have:

- $[D\varphi_x : D\varphi]_t = \lambda_{(e^{itx}, 0)}^G, \quad \delta_x^{it} = \lambda_{(e^{-2itx}, 0)}^G.$

- $(M_{-x}, \Delta_{-x}) \simeq (M_x, \Delta_x)^{op}$  and if  $x, y \geq 0$  with  $x \neq y$  then  $(M_x, \Delta_x)$  and  $(M_y, \Delta_y)$  are not isomorphic.

The von Neumann algebra of the dual quantum group  $(\widehat{M}_x, \widehat{\Delta}_x)$  is generated by two operators  $\hat{\alpha}$  and  $\hat{\beta}$  affiliated with it and such that

- $\hat{\alpha}$  is normal,  $\hat{\beta}$  is  $q$ -normal, i.e.,  $\hat{\beta}\hat{\beta}^* = q\hat{\beta}^*\hat{\beta}$ ,
- $\hat{\alpha}\hat{\beta} = \hat{\beta}\hat{\alpha}$  and  $\hat{\alpha}\hat{\beta}^* = q\hat{\beta}^*\hat{\alpha}$ , with  $q = e^{4x}$ .

The comultiplication is given by  $\widehat{\Delta}_x(\hat{\alpha}) = \hat{\alpha} \otimes \hat{\alpha}$  and  $\widehat{\Delta}_x(\hat{\beta}) = \hat{\alpha} \otimes \hat{\beta} \dot{+} \hat{\beta} \otimes 1$ .

For the dual  $(\widehat{M}_x, \widehat{\Delta}_x)$  we deform, like in the Woronowicz' quantum  $az + b$  group, the commutativity relation between the two coordinate functions, but the difference is that we also deform the normality of the second coordinate function.

The second example of Section 5 is the twisting of an already non trivial object. Consider the Woronowicz' quantum  $az + b$  group  $(M, \Delta)$  at a fixed parameter  $0 < q < 1$ . Let  $\alpha : L^\infty(\mathbb{C}^q) \rightarrow M$  be the normal faithful \*-homomorphism defined by  $\alpha(F) = F(a)$ . Because  $\Delta(a) = a \otimes a$ , one has  $\Delta \circ \alpha = (\alpha \otimes \alpha) \circ \Delta_{\mathbb{C}^q}$ . Thus, we have a co-subgroup  $\widehat{\mathbb{C}^q} < (M, \Delta)$  which is stable:

$$\sigma_t \circ \alpha(F) = \sigma_t(F(a)) = F(\sigma_t(a)) = F(q^{-2it}a) = \alpha(F(\cdot\gamma_t^{-1})),$$

where  $\gamma_t = q^{2it} \in \mathbb{C}^q$ . Performing the twisting construction with the bicharacters

$$\Psi_x(q^{k+i\varphi}, q^{l+i\psi}) = q^{ix(k\psi-l\varphi)}, \quad \forall x \in \mathbb{Z},$$

we get the twisted l.c. quantum groups  $(M_x, \Delta_x)$ . The main result of Section 5.2 is the following. Recall that we denote by  $a = u|a|$  the polar decomposition of  $a$ .

**Theorem 4** *One has  $\Delta_x(a) = a \otimes a$  and  $\Delta_x(b) = u^{-x+1}|a|^{x+1} \otimes b \dot{+} b \otimes u^x|a|^{-x}$ . The modular element  $\delta_x = |a|^{4x+2}$ , the antipode is not deformed and we have  $[D\varphi_x : D\varphi]_t = |a|^{-2ixt}$ . Moreover, for any  $x, y \in \mathbb{N}$ , one has: if  $x \neq y$ , then  $(M_x, \Delta_x)$  and  $(M_y, \Delta_y)$  are not isomorphic; if  $x \neq 0$ , then  $(M_x, \Delta_x)$  and  $(M_{-x}, \Delta_{-x})$  are not isomorphic. The von Neumann algebra of the dual quantum group  $(\widehat{M}_x, \widehat{\Delta}_x)$  is generated by two operators  $\hat{\alpha}$  and  $\hat{\beta}$  affiliated with it and such that*

- $\hat{\alpha}$  is normal,  $\hat{\beta}$  is  $p$ -normal, i.e.,  $\hat{\beta}\hat{\beta}^* = p\hat{\beta}^*\hat{\beta}$ ,
- $\hat{\alpha}\hat{\beta} = q^2\hat{\beta}\hat{\alpha}$  and  $\hat{\alpha}\hat{\beta}^* = p\hat{\beta}^*\hat{\alpha}$ , with  $p = q^{-4x}$ .

The comultiplication is given by  $\widehat{\Delta}_x(\hat{\alpha}) = \hat{\alpha} \otimes \hat{\alpha}$  and  $\widehat{\Delta}_x(\hat{\beta}) = \hat{\alpha} \otimes \hat{\beta} \dot{+} \hat{\beta} \otimes 1$ .

We refer to [5] for the explicit example of the twisting in the  $C^*$ -setting of the group  $G$  of  $2 \times 2$  upper triangular matrices of determinant 1 with the abelian subgroup of diagonal matrices in  $G$ . Next subsection contains useful technical result.

## 2.8 Abelian stable co-subgroups

Let  $\widehat{G} < (M, \Delta)$  be a stable co-subgroup with  $G$  abelian. For all  $\gamma \in \widehat{G}$ , the map  $t \mapsto \langle \gamma, \gamma_t \rangle$  is a character on  $\mathbb{R}$ , so there exists  $\lambda(\gamma) > 0$  such that  $\langle \gamma, \gamma_t \rangle = \lambda(\gamma)^{it}$  for all  $t \in \mathbb{R}$ .

**Proposition 3** *Let  $\widehat{G} < (M, \Delta)$  be a co-subgroup with  $G$  abelian. Then:*

$$1. (1 \otimes L_\gamma)W(1 \otimes L_\gamma^*) = W(L_\gamma \otimes 1), \quad (1 \otimes R_\gamma)W(1 \otimes R_\gamma^*) = (L_{-\gamma} \otimes 1)W, \quad (3)$$

for all  $\gamma \in \widehat{G}$ , so we have two commuting actions  $\alpha^L$  and  $\alpha^R$  of  $\widehat{G}$  on  $\widehat{M}$ :  $\alpha_\gamma^L(x) = L_\gamma x L_\gamma^*$  and  $\alpha_\gamma^R(x) = R_\gamma x R_\gamma^*$ . This gives an action of  $\widehat{G}^2$  on  $\widehat{M}$   $\alpha_{\gamma_1, \gamma_2} = \alpha_{\gamma_1}^L \circ \alpha_{\gamma_2}^R$  such that

$$(\iota \otimes \alpha_{\gamma_1, \gamma_2})(W) = (L_{\gamma_2}^* \otimes 1)W(L_{\gamma_1}^* \otimes 1). \quad (4)$$

2. If  $\widehat{G} < (M, \Delta)$  is stable, then, for all  $x \in \mathcal{N}_{\widehat{\varphi}}$  and all  $\gamma \in \widehat{G}$ , we have  $\alpha_\gamma^L(x), \alpha_\gamma^R(x) \in \mathcal{N}_{\widehat{\varphi}}$ ,  $L_\gamma \widehat{\Lambda}(x) = \widehat{\Lambda}(\alpha_\gamma^L(x))$ , and  $R_\gamma \widehat{\Lambda}(x) = \lambda(\gamma)^{-\frac{1}{2}} \widehat{\Lambda}(\alpha_\gamma^R(x))$ .

**Proof.** Since  $\Delta(L_\gamma) = L_\gamma \otimes L_\gamma$ ,  $\Delta(x) = W^*(1 \otimes x)W$  and  $(\widehat{J} \otimes J)W(\widehat{J} \otimes J) = W^*$ , it is easy to check the first two equalities. The equality for  $\alpha$  follows immediately. To prove the second assertion we need the following

**Lemma 3 ([8])** *Let  $\omega \in \mathcal{I}$ ,  $a \in M$ , and  $b \in \mathcal{D}(\sigma_{-\frac{i}{2}})$ , then  $a\omega b \in \mathcal{I}$  and*

$$\xi(a\omega b) = aJ\sigma_{-\frac{i}{2}}(b)^*J\xi(\omega).$$

Let us prove the second assertion. By the first assertion we have  $\alpha_\gamma^L((\omega \otimes \iota)(W)) = (L_\gamma \omega \otimes \iota)(W)$ . Take  $\omega \in \mathcal{I}$ . By Lemma 3, we have  $L_\gamma \omega \in \mathcal{I}$  and

$$\widehat{\Lambda}(\alpha_\gamma^L(\lambda(\omega))) = \widehat{\Lambda}(\lambda(L_\gamma \omega)) = L_\gamma \widehat{\Lambda}(\lambda(\omega)).$$

Because  $\lambda(\mathcal{I})$  is a core for  $\widehat{\Lambda}$ , for all  $x \in \mathcal{N}_{\widehat{\varphi}}$ , we have  $\alpha_\gamma^L(x) \in \mathcal{N}_{\widehat{\varphi}}$  and

$$\widehat{\Lambda}(\alpha_\gamma^L(x)) = L_\gamma \widehat{\Lambda}(x).$$

By the first assertion, we have  $\alpha_\gamma^R((\omega \otimes \iota)(W)) = (\omega L_{-\gamma} \otimes \iota)(W)$ . Note that  $\sigma_t(L_\gamma) = \lambda(\gamma)^{-it} L_\gamma$ , thus  $L_\gamma \in \mathcal{D}(\sigma_{\frac{i}{2}})$  and  $\sigma_{\frac{i}{2}}(L_\gamma) = \lambda(\gamma)^{\frac{1}{2}} L_\gamma$ . Take  $\omega \in \mathcal{I}$ . By Lemma 3, we have  $\omega L_{-\gamma} \in \mathcal{I}$  and

$$\widehat{\Lambda}(\alpha_\gamma^R(\lambda(\omega))) = \widehat{\Lambda}(\lambda(\omega L_{-\gamma})) = \lambda(\gamma)^{\frac{1}{2}} R_\gamma \widehat{\Lambda}(\lambda(\omega)).$$

Because  $\lambda(\mathcal{I})$  is a core for  $\widehat{\Lambda}$ , this concludes the proof. ■

### 3 Twisting of locally compact quantum groups

Let  $G$  be a l.c. group and  $(M, \Delta)$  a l.c. quantum group. Suppose that  $\widehat{G} < (M, \Delta)$  is a stable co-subgroup. We keep the notations of Section 2.7. Note that the maps  $(t \mapsto \alpha(\Psi(\cdot, \gamma_t^{-1})))$  and  $(t \mapsto \alpha(\Psi(\gamma_s^{-1}, \cdot)))$  are unitary representations of  $\mathbb{R}$  in  $M$ . Let  $A$  and  $B$  be the positive self-adjoint operators affiliated with  $M$  such that  $A^{it} = \alpha(\Psi(\cdot, \gamma_t^{-1}))$  and  $B^{is} = \alpha(\Psi(\gamma_s^{-1}, \cdot))$ . We have  $\Delta(A) = A \otimes A$ ,  $\Delta(B) = B \otimes B$ . Note that  $\sigma_t(A^{is}) = \alpha(\Psi(\cdot, \gamma_t^{-1}, \gamma_s^{-1})) = \lambda^{ist} A^{is}$ . Also we have  $\sigma'_s(B^{it}) = \sigma_s(B^{it}) = \lambda^{ist} B^{it}$ , so the weights  $\varphi_\Omega$  and  $\psi_\Omega$  are the Vaes' weights associated with  $\varphi$ ,  $\lambda$  and  $A$ , and with  $\psi$ ,  $\lambda$  and  $B$ , respectively. In the sequel, we denote by  $\Lambda_\Omega$  the canonical G.N.S. map associated with  $\varphi_\Omega$ , and by  $F \mapsto \tilde{F}$  the \*-automorphism of  $L^\infty(G \times G)$  defined by  $\tilde{F}(g, h) = F(g^{-1}, gh)$ . Theorem 1 is in fact a corollary of the following result.

**Theorem 5** *For all  $x, y \in \mathcal{N}_{\varphi_\Omega}$ , we have  $\Delta_\Omega(x)(y \otimes 1) \in \mathcal{N}_{\varphi_\Omega \otimes \varphi_\Omega}$  and*

$$(\Lambda_\Omega \otimes \Lambda_\Omega)(\Delta_\Omega(x)(y \otimes 1)) = W_\Omega^*(\Lambda_\Omega(y) \otimes \Lambda_\Omega(x)),$$

where  $W_\Omega^* = \Omega(\hat{J} \otimes J)W\tilde{\Omega}(\hat{J} \otimes J)$ .

**Proof.** Let us introduce the sets

$$N = \left\{ x \in M, xA^{\frac{1}{2}} \text{ is bounded and } \overline{xA^{\frac{1}{2}}} \in \mathcal{N}_\varphi \right\} \quad \text{and}$$

$$L = \left\{ x \in N, A^{-\frac{1}{2}}\overline{xA^{\frac{1}{2}}} \text{ is bounded and } \Lambda(\overline{xA^{\frac{1}{2}}}) \in \mathcal{D}(A^{-\frac{1}{2}}) \right\}.$$

When  $y \in L$ , we denote the closure of  $A^{-\frac{1}{2}}\overline{xA^{\frac{1}{2}}}$  by  $\overline{A^{-\frac{1}{2}}yA^{\frac{1}{2}}}$ . By definition,  $N$  is a  $\sigma$ -strong\*-norm core for  $\Lambda_\Omega$ , and Proposition 18 shows that the same is true for  $L$ . As  $\Lambda_\Omega$  is closed in these topologies, it suffices to prove the theorem for elements  $x \in N$  and  $y \in L$ . The first step is as follows.

**Lemma 4** *Let  $x \in N$ ,  $y \in L$  and  $F \in (\alpha \otimes \alpha)(L^\infty(G \times G))$ . Then*

$$\begin{aligned} & (\Delta(x)F^*y \otimes 1)(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}}) \quad \text{is bounded and} \\ & \overline{(\Delta(x)F^*(y \otimes 1))(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}})} = \Delta(\overline{xA^{\frac{1}{2}}})F^* \left( \overline{A^{-\frac{1}{2}}yA^{\frac{1}{2}} \otimes 1} \right). \end{aligned}$$

**Proof.** Note that  $\Delta(A^{\frac{1}{2}}) = A^{\frac{1}{2}} \otimes A^{\frac{1}{2}} = W^*(1 \otimes A^{\frac{1}{2}})W$ . Let  $x \in N$  and  $\xi \in \mathcal{D}(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}})$ . Then  $W\xi \in \mathcal{D}(1 \otimes A^{\frac{1}{2}})$  and

$$\begin{aligned} \Delta(x)(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}})\xi &= W^*(1 \otimes x)WW^*(1 \otimes A^{\frac{1}{2}})W\xi \\ &= W^*(1 \otimes x)(1 \otimes A^{\frac{1}{2}})W\xi \\ &= W^*(1 \otimes \overline{xA^{\frac{1}{2}}})W\xi = \Delta(\overline{xA^{\frac{1}{2}}})\xi. \end{aligned}$$

Thus,  $\Delta(x)(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}}) \subset \overline{\Delta(xA^{\frac{1}{2}})}$  and because it is densely defined, we have shown that,  $\forall x \in N$ ,  $\Delta(x)(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}})$  is bounded and  $\Delta(x)(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}}) = \overline{\Delta(xA^{\frac{1}{2}})}$ . If  $x \in N$ ,  $y \in N'$ , the commutativity of  $(\alpha \otimes \alpha)(L^\infty(G \times G))$  implies:

$$\begin{aligned} (\Delta(x)F^*(y \otimes 1))(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}}) &= \Delta(x)(1 \otimes A^{\frac{1}{2}})F^*(yA^{\frac{1}{2}} \otimes 1) \\ &= \Delta(x)(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}})(A^{-\frac{1}{2}} \otimes 1)F^*(yA^{\frac{1}{2}} \otimes 1) \\ &= \Delta(x)(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}})F^*(A^{-\frac{1}{2}}yA^{\frac{1}{2}} \otimes 1) \\ &\subset \overline{\Delta(xA^{\frac{1}{2}})F^*(A^{-\frac{1}{2}}yA^{\frac{1}{2}} \otimes 1)}. \end{aligned}$$

Since  $(\Delta(x)F^*(y \otimes 1))(A^{\frac{1}{2}} \otimes A^{\frac{1}{2}})$  is densely defined, the proof is finished.  $\blacksquare$  In what follows, we identify  $L^\infty(G)$  with its image  $\alpha(L^\infty(G))$ . Note that

$$(\iota \otimes \sigma_t)(\tilde{F}) = \widetilde{(\iota \otimes \sigma_t)(F)}, \quad \text{for all } t \in \mathbb{R}, F \in L^\infty(G \times G).$$

By analytic continuation, this is also true for  $t = z \in \mathbb{C}$  and  $F \in \mathcal{D}(\iota \otimes \sigma_z)$ .

Now we construct a set of certain elements of  $\mathcal{N}_{\varphi_\Omega \otimes \varphi_\Omega}$  and give their images by  $\Lambda_\Omega \otimes \Lambda_\Omega$ .

**Lemma 5** *Let  $x \in N$ ,  $y \in L$  and  $F \in L^\infty(G \times G)$ . If  $F \in \mathcal{D}(\iota \otimes \sigma_{-\frac{i}{2}})$  then*

$$\Delta(x)F^*(y \otimes 1) \in \mathcal{N}_{\varphi_\Omega \otimes \varphi_\Omega} \quad \text{and}$$

$$(\Lambda_\Omega \otimes \Lambda_\Omega)(\Delta(x)F^*(y \otimes 1)) = (\hat{J} \otimes J)W(\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{F})(\hat{J} \otimes J) \left( A^{-\frac{1}{2}}\Lambda_\Omega(y) \otimes \Lambda_\Omega(x) \right).$$

**Proof.** According to Proposition 20 and Lemma 4, it suffices to show that

$$\begin{aligned} \forall F \in \mathcal{D}(\iota \otimes \sigma_{-\frac{i}{2}}), \overline{\Delta(xA^{\frac{1}{2}})F^*(A^{-\frac{1}{2}}yA^{\frac{1}{2}} \otimes 1)} &\in \mathcal{N}_{\varphi \otimes \varphi} \quad \text{and,} \\ (\Lambda \otimes \Lambda) \left( \overline{\Delta(xA^{\frac{1}{2}})F^*(A^{-\frac{1}{2}}yA^{\frac{1}{2}} \otimes 1)} \right) & \tag{5} \\ = (\hat{J} \otimes J)W(\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{F})(\hat{J} \otimes J) & \left( A^{-\frac{1}{2}}\Lambda_\Omega(y) \otimes \Lambda_\Omega(x) \right). \end{aligned}$$

Let  $F \in L^\infty(G \times G)$ . We identify  $\sigma$  with its restriction to  $L^\infty(G)$ . A direct application of Lemma 1 (2) gives that  $L^\infty(G) \odot \mathcal{D}(\sigma_{-\frac{i}{2}})$  is a  $\sigma$ -strong\* core for  $\iota \otimes \sigma_{-\frac{i}{2}}$ . Taking into account the observation preceding this lemma and because  $\Lambda \otimes \Lambda$  is  $\sigma$ -strong\*-norm closed, it suffices to show (5) for  $F \in L^\infty(G) \odot \mathcal{D}(\sigma_{-\frac{i}{2}})$ . By linearity, we only have to show (5) for  $F$  of the form  $F = \overline{F_1} \otimes F_2$  with  $F_1, F_2 \in L^\infty(G)$  and  $F_2 \in \mathcal{D}(\sigma_{-\frac{i}{2}})$ . Proposition 18 gives  $A^{-\frac{1}{2}}yA^{\frac{1}{2}} \in \mathcal{N}_\varphi$ , so  $\overline{\Delta(xA^{\frac{1}{2}})(F_1^*A^{-\frac{1}{2}}yA^{\frac{1}{2}} \otimes 1)} \in \mathcal{N}_{\varphi \otimes \varphi}$ , and writing

$$\overline{\Delta(xA^{\frac{1}{2}})(F_1^* \otimes F_2^*)(A^{-\frac{1}{2}}yA^{\frac{1}{2}} \otimes 1)} = \overline{\Delta(xA^{\frac{1}{2}})(F_1^*A^{-\frac{1}{2}}yA^{\frac{1}{2}} \otimes 1)}(1 \otimes F_2^*)$$

with  $1 \otimes F_2 \in \mathcal{D}(\iota \otimes \sigma_{-\frac{i}{2}})$ , we see that  $\Delta(\overline{xA^{\frac{1}{2}}})F^*(\overline{A^{-\frac{1}{2}}yA^{\frac{1}{2}}} \otimes 1) \in \mathcal{N}_{\varphi \otimes \varphi}$  and

$$\begin{aligned}
& (\Lambda \otimes \Lambda) \left( \Delta(\overline{xA^{\frac{1}{2}}})F^*(\overline{A^{-\frac{1}{2}}yA^{\frac{1}{2}}} \otimes 1) \right) \\
&= \left( 1 \otimes J\sigma_{-\frac{i}{2}}(F_2)J \right) (\Lambda \otimes \Lambda) \left( \Delta(\overline{xA^{\frac{1}{2}}})(F_1^* \overline{A^{-\frac{1}{2}}yA^{\frac{1}{2}}} \otimes 1) \right) \\
&= \left( 1 \otimes J\sigma_{-\frac{i}{2}}(F_2)J \right) W^* \Lambda(F_1^* \overline{A^{-\frac{1}{2}}yA^{\frac{1}{2}}}) \otimes \Lambda(\overline{xA^{\frac{1}{2}}}) \\
&\quad (\text{by definition of } W) \\
&= \left( 1 \otimes J\sigma_{-\frac{i}{2}}(F_2)J \right) (\hat{J} \otimes J)W(\hat{J} \otimes J)(F_1^* \otimes 1)\Lambda(\overline{A^{-\frac{1}{2}}yA^{\frac{1}{2}}}) \otimes \Lambda(\overline{xA^{\frac{1}{2}}}) \\
&\quad (\text{because } W^* = (\hat{J} \otimes J)W(\hat{J} \otimes J)) \\
&= (\hat{J} \otimes J) \left( 1 \otimes \sigma_{-\frac{i}{2}}(F_2) \right) W(R(F_1) \otimes 1) (\hat{J} \otimes J)A^{-\frac{1}{2}}\Lambda_{\Omega}(y) \otimes \Lambda_{\Omega}(x) \\
&\quad (\text{because } R(x) = \hat{J}x^*\hat{J}, \text{ and } \Lambda(\overline{A^{-\frac{1}{2}}yA^{\frac{1}{2}}}) = A^{-\frac{1}{2}}\Lambda_{\Omega}(y) \text{ by Proposition 18}) \\
&= (\hat{J} \otimes J)W\Delta \left( \sigma_{-\frac{i}{2}}(F_2) \right) (R(F_1) \otimes 1) (\hat{J} \otimes J)A^{-\frac{1}{2}}\Lambda_{\Omega}(y) \otimes \Lambda_{\Omega}(x) \\
&\quad (\text{because } \Delta(x) = W^*(1 \otimes x)W).
\end{aligned}$$

So we just have to compute:

$$\begin{aligned}
\Delta \left( \sigma_{-\frac{i}{2}}(F_2) \right) (R(F_1) \otimes 1)(g, h) &= F_1(g^{-1})\sigma_{-\frac{i}{2}}(F_2)(gh) \\
&= (\iota \otimes \sigma_{-\frac{i}{2}})(F)(g^{-1}, gh) = (\iota \otimes \widetilde{\sigma_{-\frac{i}{2}}})(F)(g, h).
\end{aligned}$$

■ The next lemma is necessary to finish the proof of the theorem.

**Lemma 6**

(1) We have  $\hat{J}A^{-\frac{1}{2}} = A^{\frac{1}{2}}\hat{J}$ .

(2) The operator  $(\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{\Omega})$  is normal, affiliated with  $M \otimes M$ , and its polar decomposition is

$$(\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{\Omega}) = \tilde{\Omega}(A^{-\frac{1}{2}} \otimes 1).$$

**Proof.** Let  $\alpha \in \mathbb{R}$  and  $\mathcal{D}_{\alpha}$  the horizontal strip bounded by  $\mathbb{R}$  and  $\mathbb{R} - i\alpha$ .

(1) Let  $\xi \in \mathcal{D}(A^{-\frac{1}{2}})$ . There exists a continuous bounded extension  $F$  of  $t \mapsto A^{it}\xi$  on  $\mathcal{D}_{-\frac{1}{2}}$  which is analytic on  $\mathcal{D}_{-\frac{1}{2}}^0$ . The function  $G(z) = \hat{J}F(\bar{z})$  is continuous bounded on  $\mathcal{D}_{\frac{1}{2}}$  and analytic on  $\mathcal{D}_{\frac{1}{2}}^0$ . Moreover :

$$R(A^{-it})(g) = \Psi(g^{-1}, \gamma_t) = \Psi(g, \gamma_t^{-1}) = A^{it}(g), \quad \text{for all } g \in G, t \in \mathbb{R}.$$

Thus,  $\hat{J}A^{it}\hat{J} = R(A^{-it}) = A^{it}$ . We deduce  $G(t) = \hat{J}A^{it}\xi = A^{it}\hat{J}\xi$ . This means that  $\hat{J}\xi \in \mathcal{D}(A^{\frac{1}{2}})$  and  $A^{\frac{1}{2}}\hat{J}\xi = G(-\frac{i}{2}) = \hat{J}F(\frac{i}{2}) = \hat{J}A^{-\frac{1}{2}}\xi$ , so  $\hat{J}A^{-\frac{1}{2}} \subset A^{\frac{1}{2}}\hat{J}$ . The other inclusion can be proved in the same way.

(2) Note that

$$(\iota \otimes \sigma_t)(\tilde{\Omega})(g, h) = \Psi(g^{-1}, gh\gamma_t^{-1}) = \Psi(g^{-1}, gh)\Psi(g, \gamma_t) = \tilde{\Omega}(A^{-it} \otimes 1)(g, h).$$

We conclude the proof applying Proposition 1.  $\blacksquare$

We can now prove the theorem. Let  $x \in N$  and  $y \in L$ . Put  $\xi = \hat{J}\Lambda_\Omega(y) \in \mathcal{D}(A^{\frac{1}{2}})$  and  $\eta = J\Lambda_\Omega(x)$ . By Lemma 6 (2),  $A^{\frac{1}{2}}\xi \otimes \eta \in \mathcal{D}\left((\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{\Omega})\right)$ . Thus, using Lemma 1 (1), there exists  $\tilde{\Omega}_n \in L^\infty(G \times G) \cap \mathcal{D}(\iota \otimes \sigma_{-\frac{i}{2}})$  such that

$$\tilde{\Omega}_n \rightarrow \tilde{\Omega} \quad \sigma\text{-strongly}^* \quad \text{and} \quad (\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{\Omega}_n)(A^{\frac{1}{2}}\xi \otimes \eta) \rightarrow (\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{\Omega})(A^{\frac{1}{2}}\xi \otimes \eta).$$

Because  $\tilde{F} = F$ , we also have  $\Omega_n \rightarrow \Omega$   $\sigma$ -strongly\*, so

$$\Delta(x)\Omega_n^*(y \otimes 1) \rightarrow \Delta(x)\Omega^*y \otimes 1 \quad \sigma\text{-strongly}^*.$$

By Lemma 5,  $\Delta(x)\Omega_n^*(y \otimes 1) \in \mathcal{N}_{\varphi_\Omega \otimes \varphi_\Omega}$  and

$$\begin{aligned} (\Lambda_\Omega \otimes \Lambda_\Omega)(\Delta(x)\Omega_n^*(y \otimes 1)) &= (\hat{J} \otimes J)W(\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{\Omega}_n)(\hat{J} \otimes J)\left(A^{-\frac{1}{2}}\Lambda_\Omega(y) \otimes \Lambda_\Omega(x)\right) \\ &= (\hat{J} \otimes J)W(\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{\Omega}_n)(A^{\frac{1}{2}}\xi \otimes \eta) \quad (\text{by Lemma 6(1)}) \\ &\rightarrow (\hat{J} \otimes J)W(\iota \otimes \sigma_{-\frac{i}{2}})(\tilde{\Omega})(A^{\frac{1}{2}}\xi \otimes \eta) \\ &= (\hat{J} \otimes J)W\tilde{\Omega}(\xi \otimes \eta) \quad (\text{by Lemma 6(2)}) \\ &= (\hat{J} \otimes J)W\tilde{\Omega}(\hat{J} \otimes J)(\Lambda_\Omega(y) \otimes \Lambda_\Omega(x)). \end{aligned}$$

Because  $\Lambda_\Omega \otimes \Lambda_\Omega$  is  $\sigma$ -strong\* - norm closed, we have  $\Delta(x)\Omega^*(y \otimes 1) \in \mathcal{N}_{\varphi_\Omega \otimes \varphi_\Omega}$ , so  $\Delta_\Omega(x)(y \otimes 1) \in \mathcal{N}_{\varphi_\Omega \otimes \varphi_\Omega}$  and

$$\begin{aligned} (\Lambda_\Omega \otimes \Lambda_\Omega)(\Delta_\Omega(x)(y \otimes 1)) &= \Omega(\Lambda_\Omega \otimes \Lambda_\Omega)(\Delta(x)\Omega^*(y \otimes 1)) \\ &= \Omega(\hat{J} \otimes J)W\tilde{\Omega}(\hat{J} \otimes J)(\Lambda_\Omega(y) \otimes \Lambda_\Omega(x)) \\ &= W_\Omega^*(\Lambda_\Omega(y) \otimes \Lambda_\Omega(x)). \end{aligned}$$

Let  $R_\Omega = uR(x)u^*$  be the \*-anti-automorphism of  $M$ , where  $u = \alpha(\Psi(\cdot^{-1}, \cdot))$ .  $\blacksquare$

*Proof of Theorem 1.* Let  $x, y \in \mathcal{N}_{\varphi_\Omega}$ . By Theorem 5, we have

$$\begin{aligned} \|(\Lambda_\Omega \otimes \Lambda_\Omega)(\Delta_\Omega(x)y \otimes 1)\|^2 &= \|\Lambda_\Omega(y) \otimes \Lambda_\Omega(x)\|^2 \\ \Leftrightarrow (\omega_{\Lambda_\Omega(y)} \otimes \varphi_\Omega)(\Delta_\Omega(x^*x)) &= \omega_{\Lambda_\Omega(y)}(1)\varphi_\Omega(x^*x). \end{aligned} \quad (6)$$

Let  $\omega \in M_*$ ,  $\omega \geq 0$ . The inclusion  $M \subset \mathcal{B}(H)$  is standard, so there is  $\xi \in H$  such that  $\omega = \omega_\xi$ . Let  $a_i \in M$  such that  $\Lambda_\Omega(a_i) \rightarrow \xi$ . Then

$$\omega_{\Lambda_\Omega(a_i)}(x) \rightarrow \omega(x), \quad \text{for all } x \in M. \quad (7)$$

To show that  $\varphi_\Omega$  is left invariant, it suffices to show that  $\Delta_\Omega(x^*x) \in \mathcal{N}_{\iota \otimes \varphi_\Omega}$  when  $x \in \mathcal{N}_{\varphi_\Omega}$ . Indeed, in this case we have, using (7),

$$\begin{aligned} \omega_{\Lambda_\Omega(a_i)}(1)\varphi_\Omega(x^*x) &\rightarrow \omega(1)\varphi_\Omega(x^*x) \quad \text{and,} \\ (\omega_{\Lambda_\Omega(a_i)} \otimes \varphi_\Omega)(\Delta_\Omega(x^*x)) &\rightarrow (\omega \otimes \varphi_\Omega)(\Delta_\Omega(x^*x)). \end{aligned}$$

This implies, using (6), that for all  $\omega \in M_*^+$  and  $x \in \mathcal{N}_{\varphi_\Omega}$ ,

$$(\omega \otimes \varphi_\Omega)(\Delta_\Omega(x^*x)) = \omega(1)\varphi_\Omega(x^*x),$$

i.e.,  $\varphi_\Omega$  is left invariant. Let us show that  $\Delta_\Omega(x^*x) \in \mathcal{N}_{\iota \otimes \varphi_\Omega}$ . We put

$$m = (\iota \otimes \varphi_\Omega)(\Delta_\Omega(x^*x)) \in M_+^{\text{ext}}.$$

The spectral decomposition of  $m$  is  $m = \int_0^\infty \lambda de_\lambda + \infty \cdot p$ . From (6) we see that, for all  $y \in \mathcal{N}_{\varphi_\Omega}$ ,  $m(\omega_{\Lambda_\Omega}(y)) < \infty$ . Thus, the set  $\{\omega \in M_*^+ \mid m(\omega) < \infty\}$  is dense in  $M_*^+$ . This implies  $p = 0$  and  $m = m_T$ , where  $T$  is the positive operator affiliated with  $M$  defined by

$$T = \int_0^\infty \lambda de_\lambda.$$

So, we only have to show that  $T$  is a bounded operator. Using again (6) and the definition of  $m_T$ , we see that, for all  $y \in \mathcal{N}_{\varphi_\Omega}$ ,  $\Lambda_\Omega(y) \in \mathcal{D}(A^{\frac{1}{2}})$  and

$$\|T^{\frac{1}{2}}\Lambda_\Omega(y)\|^2 = \varphi_\Omega(x^*x)\|\Lambda_\Omega(y)\|^2.$$

Thus,  $T$  is a bounded operator.

It is easy to check (see [16]) that  $\Delta_\Omega \circ R_\Omega = \sigma(R_\Omega \otimes R_\Omega)\Delta_\Omega$ , so the right invariance of  $\varphi_\Omega \circ R_\Omega$  follows. Thus,  $(M, \Delta_\Omega)$  is a l.c. quantum group and it follows immediately from Theorem 5 that  $W_\Omega$  is its multiplicative unitary. Our next aim is to show that  $\psi_\Omega = \varphi_\Omega \circ R_\Omega$ . We compute:

$$\begin{aligned} R(u\sigma_{-t}^\Omega(u^*))(g) &= u(g^{-1})u^*(g^{-1}\gamma_t) = u(g)\Psi(g^{-1}\gamma_t, g^{-1}\gamma_t) \\ &= u(g)u^*(g)\Psi(g^{-1}, \gamma_t)\Psi(\gamma_t, g^{-1})\Psi(\gamma_t, \gamma_t) \\ &= \lambda^{it^2}(A^{it}B^{it})(g). \end{aligned}$$

This implies

$$\begin{aligned} [D\varphi_\Omega \circ R_\Omega : D\psi]_t &= [D(\varphi_\Omega)_u \circ R : D\varphi \circ R]_t = R([D(\varphi_\Omega)_u : D\varphi]_{-t}^*) \\ &= R([D(\varphi_\Omega)_u : D\varphi_\Omega]_{-t}^*) R([D\varphi_\Omega : D\varphi]_{-t}^*) \\ &= R(u\sigma_{-t}^\Omega(u^*)) R\left(\lambda^{-i\frac{t^2}{2}}A^{it}\right) \\ &= \lambda^{it^2}A^{it}B^{it}(\lambda^{-i\frac{t^2}{2}}A^{-it}) \\ &= \lambda^{i\frac{t^2}{2}}B^{it}. \end{aligned}$$

Thus,  $\psi_\Omega = \varphi_\Omega \circ R_\Omega$ . In order to finish the proof, we have to compute the scaling group and the scaling constant. Recall that if  $(M, \Delta)$  is a l.c. quantum group, then the scaling group is the unique one-parameter group  $\tau_t$  on  $M$  such

that  $\Delta \circ \sigma_t = (\tau_t \otimes \sigma_t) \circ \Delta$ . Since  $(\iota \otimes \sigma_t)(\Omega) = \Omega(A^{it} \otimes 1)$ , using  $\tau_t \circ \alpha = \alpha$ , we have  $(\tau_t \otimes \sigma_t)(\Omega) = \Omega(A^{it} \otimes 1)$ , which gives:

$$\begin{aligned} (\tau_t \otimes \sigma_t^\Omega)(\Delta_\Omega(x)) &= (1 \otimes A^{it})(\tau_t \otimes \sigma_t)(\Omega)(\tau_t \otimes \sigma_t)(\Delta(x))(\tau_t \otimes \sigma_t)(\Omega^*)(1 \otimes A^{-it}) \\ &= \Omega(A^{it} \otimes A^{it})(\tau_t \otimes \sigma_t)(\Delta(x))(A^{-it} \otimes A^{-it})\Omega^* \\ &= \Omega\Delta(A^{it})\Delta(\sigma_t(x))\Delta(A^{-it})\Omega^* \\ &= \Delta_\Omega(\sigma_t^\Omega(x)). \end{aligned}$$

This relation characterizes the scaling group of  $(M, \Delta_\Omega)$ . Recall that the scaling constant of  $(M, \Delta)$  verifies  $\varphi \circ \tau_t = \nu^{-t}\varphi$ . Because  $\tau_t(A^{is}) = A^{is}$ , for all  $t, s \in \mathbb{R}$ , we deduce that  $\varphi_\Omega \circ \tau_t^\Omega = \varphi_\Omega \circ \tau_t = \nu^{-t}\varphi_\Omega$ . Thus,  $\nu^\Omega = \nu$ .

Let us denote by  $X$  and  $Y$  the operators

$$X = \Omega^* \quad \text{and} \quad Y = (\hat{J} \otimes J)(u^* \otimes 1)\Omega(\hat{J} \otimes J).$$

Note that  $\tilde{\Psi}^*(g, h) = \Psi^*(g^{-1}, g)\Psi(g, h)$ , so  $\tilde{\Omega}^* = (u^* \otimes 1)\Omega$  and

$$W_\Omega = (\hat{J} \otimes J)\tilde{\Omega}^*W^*(\hat{J} \otimes J)\Omega^* = (\hat{J} \otimes J)\tilde{\Omega}^*(\hat{J} \otimes J)W\Omega^* = YWX.$$

From now on we suppose that  $G$  is abelian, we switch to the additive notations for its operations and denote by  $\hat{G}$  its dual. Recall that the notations  $u_\gamma$ ,  $L_\gamma$  and  $R_\gamma$  were introduced in Section 2.7. Note that  $R(L_\gamma) = L_\gamma^* = L_{-\gamma}$ .

**Proposition 4**  *$R_\Omega$  is the unitary antipode of  $(M, \Delta_\Omega)$ . Moreover,*

- $\delta_\Omega = \delta A^{-1}B$ ,
- $\mathcal{D}(S_\Omega) = \mathcal{D}(S)$  and, for all  $x \in \mathcal{D}(S)$ ,  $S_\Omega(x) = uS(x)u^*$ .

**Proof.** If  $(M, \Delta)$  is a l.c. quantum group, then the unitary antipode is the unique \*-anti-automorphism  $R$  of  $M$  such that  $R((\iota \otimes \omega_{\xi, \eta})(W)) = (\iota \otimes \omega_{J\xi, J\eta})(W)$ . Let us define two \*-homomorphisms by

$$\begin{aligned} \pi' : L^\infty(G \times G) &\rightarrow M \otimes M' : \pi'(F) = (\hat{J} \otimes J)(\alpha \otimes \alpha)(F)^*(\hat{J} \otimes J), \\ \pi : L^\infty(G \times G) &\rightarrow M \otimes M : \pi(F) = (\alpha \otimes \alpha)(F). \end{aligned}$$

We want to prove that, for all  $F, G \in L^\infty(G \times G)$  and  $\xi, \eta \in H$ ,

$$R\left((\iota \otimes \omega_{\xi, \eta})\left(\pi'(F)W\pi(G)\right)\right) = (\iota \otimes \omega_{J\xi, J\eta})\left(\pi'(G)W\pi(F)\right). \quad (8)$$

By linearity and continuity, it suffices to prove (8) for  $F = u_{\gamma_1} \otimes u_{\gamma_2}$  and  $G = u_{\gamma_3} \otimes u_{\gamma_4}$  with  $\gamma_i \in \hat{G}$ . We have

$$\pi'(u_{\gamma_1} \otimes u_{\gamma_2}) = L_{-\gamma_1} \otimes R_{-\gamma_2} \quad \text{and} \quad \pi(u_{\gamma_3} \otimes u_{\gamma_4}) = L_{\gamma_3} \otimes L_{\gamma_4}, \quad \text{so}$$

$$\begin{aligned}
& R\left((\iota \otimes \omega_{\xi, \eta})\left(\pi'(u_{\gamma_1} \otimes u_{\gamma_2})W\pi(u_{\gamma_3} \otimes u_{\gamma_4})\right)\right) \\
= & R((\iota \otimes \omega_{\xi, \eta})(L_{-\gamma_1} \otimes R_{-\gamma_2}WL_{\gamma_3} \otimes L_{\gamma_4})) \\
= & R(L_{-\gamma_1}(\iota \otimes L_{\gamma_4}\omega_{\xi, \eta}R_{-\gamma_2})(W)L_{\gamma_3}) \\
= & L_{-\gamma_3}R((\iota \otimes \omega_{L_{\gamma_4}\xi, R_{\gamma_2}\eta})(W))L_{\gamma_1} \\
= & L_{-\gamma_3}(\iota \otimes \omega_{JR_{\gamma_2}\eta, JL_{\gamma_4}\xi})(W)L_{\gamma_1} \\
= & L_{-\gamma_3}(\iota \otimes \omega_{L_{\gamma_2}J\eta, R_{\gamma_4}J\xi})(W)L_{\gamma_1} \\
= & (\iota \otimes L_{\gamma_2}\omega_{J\eta, J\xi}R_{-\gamma_4})(L_{-\gamma_3} \otimes 1WL_{\gamma_1} \otimes 1) \\
= & (\iota \otimes \omega_{J\eta, J\xi})(L_{-\gamma_3} \otimes R_{-\gamma_4}WL_{\gamma_1} \otimes L_{\gamma_2}) \\
= & (\iota \otimes \omega_{J\eta, J\xi})\left(\pi'(u_{\gamma_3} \otimes u_{\gamma_4})W\pi(u_{\gamma_1} \otimes u_{\gamma_2})\right).
\end{aligned}$$

Note that  $Y = \pi'(\tilde{\Psi})$ ,  $X = \pi(\Psi^*)$  and  $\pi(\tilde{\Psi})(u^* \otimes 1) = \tilde{\Omega}(u^* \otimes 1) = \Omega^* = X$ . Also, using  $R(u^*) = u^*$ , we have

$$\begin{aligned}
(u \otimes 1)\pi'(\Psi^*) &= (u \otimes 1)(\hat{J} \otimes J)\Omega(\hat{J} \otimes J) \\
&= (\hat{J} \otimes J)(R(u^*) \otimes 1)\Omega(\hat{J} \otimes J) \\
&= (\hat{J} \otimes J)(u^* \otimes 1)\Omega(\hat{J} \otimes J) \\
&= (\hat{J} \otimes J)\tilde{\Omega}^*(\hat{J} \otimes J) = Y.
\end{aligned}$$

Using these remarks and relation (8), one has

$$\begin{aligned}
R_{\Omega}((\iota \otimes \omega_{\xi, \eta})(W_{\Omega})) &= uR\left((\iota \otimes \omega_{\xi, \eta})\left(\pi'(\tilde{\Psi})W\pi(\Psi^*)\right)\right)u^* \\
&= (\iota \otimes \omega_{J\eta, J\xi})\left((u \otimes 1)\pi'(\Psi^*)W\pi(\tilde{\Psi})(u^* \otimes 1)\right) \\
&= (\iota \otimes \omega_{J\eta, J\xi})(YWX) \\
&= (\iota \otimes \omega_{J_{\Omega}\eta, J_{\Omega}\xi})(W_{\Omega}).
\end{aligned}$$

Where we use, in the last equality, the fact that  $J_{\Omega} = \lambda^{\frac{i}{8}}J$  so  $\omega_{J_{\Omega}\eta, J_{\Omega}\xi} = \omega_{J\eta, J\xi}$ . This relation characterizes the unitary antipode of  $(M, \Delta_{\Omega})$ . We have

$$\begin{aligned}
[D\psi_{\Omega} : D\varphi_{\Omega}]_t &= [D\psi_{\Omega} : D\psi]_t[D\psi : D\varphi]_t[D\varphi : D\varphi_{\Omega}]_t \\
&= (\lambda^{i\frac{t}{2}}B^{it})(\nu^{i\frac{t}{2}}\delta^{it})(\lambda^{-i\frac{t}{2}}A^{-it}) \\
&= \nu^{i\frac{t}{2}}(\delta A^{-1}B)^{it}.
\end{aligned}$$

Thus,  $\delta_{\Omega} = \delta A^{-1}B$  (because we have seen in the proof of Theorem 1 that  $\psi_{\Omega} = \varphi_{\Omega} \circ R_{\Omega}$ ). The last statement is clear.  $\blacksquare$

**Remark.** If  $(M, \Delta)$  is a Kac algebra,  $(M, \Delta_{\Omega})$  is not in general a Kac algebra (see Section 5.1). However, in the case considered in [3], [16], and [6], when

$\alpha(L^\infty(G))$  belongs to the fixed point subalgebra of  $M$  with respect to  $\sigma_t$ , then  $\gamma_t$  is trivial and we have  $A^{-1}B = 1$ , so  $(M, \Delta_\Omega)$  is a Kac algebra.

**Remark.** The map  $L^\infty(G \times G) \rightarrow \mathcal{B}(H \otimes H) : F \mapsto \pi'(\widehat{F})W\pi(F^*)$  is  $\sigma$ -strong\*- $\sigma$ -weak continuous. So, if  $(x \mapsto \Psi_x)$  is  $\sigma$ -strongly\* continuous map from  $\mathbb{R}$  to  $L^\infty(G \times G)$  such that  $\Psi_x$  is a continuous bicharacter, for all  $x \in \mathbb{R}$ , then, denoting by  $W_x$  the multiplicative unitary of the twisted l.c. quantum group associated with  $\Psi_x$ , the map  $x \mapsto W_x$  from  $\mathbb{R}$  to the unitaries of  $\mathcal{B}(H \otimes H)$  is  $\sigma$ -weakly continuous. This is the case for the example of section 5.1 and for the examples constructed in [5] and [6].

## 4 Rieffel's deformations of locally compact quantum group

This section is devoted to the proof of Theorem 2. We use the hypotheses and notations from the previous section and from Section 2.7. So let  $\widehat{G} < (M, \Delta)$  be a stable co-subgroup with  $G$  abelian. Recall that we have (see Section 2.8) two unitary representations of  $\widehat{G} : \gamma \mapsto L_\gamma$  and  $\gamma \mapsto R_\gamma$  of  $\widehat{G}$ . This gives two \*-homomorphisms from  $L^\infty(G)$  to  $\mathcal{B}(H)$ ,  $\pi_L$  and  $\pi_R$ , respectively. We have

$$\pi_L = \alpha \quad \text{and} \quad \pi_R(F) = J\alpha(\overline{F(-\cdot)})J = J\widehat{J}\alpha(F)\widehat{J}.$$

Recall that  $W_\Omega = YWX$ , where  $X = (\alpha \otimes \alpha)(\Psi^*) = (\pi_L \otimes \pi_L)(\Psi^*)$  and  $Y = (\widehat{J} \otimes J)\widehat{\Omega}^*(\widehat{J} \otimes J) = (\pi_L \otimes \pi_R)(\widehat{\Psi}) = (\alpha(u) \otimes 1)(\pi_L \otimes \pi_R)(\Psi^*)$ . Note that  $\widehat{G} < (M_\Omega, \Delta_\Omega)$  is also stable (by the preceding section), so the results of section 2.8 can be applied also to  $\widehat{G} < (M_\Omega, \Delta_\Omega)$ . Thus, we have a left-right action  $\alpha$  of  $\widehat{G}^2$  on  $\widehat{M}$  and also a left-right action  $\beta$  of  $\widehat{G}^2$  on  $\widehat{M}_\Omega$ . We denote by the same  $\pi$  the canonical morphism from  $\widehat{M}$  in the crossed product  $N = \widehat{G}^2 \ltimes \widehat{M}$  and from  $\widehat{M}_\Omega$  in  $\widehat{G}^2 \ltimes \widehat{M}_\Omega$ . Also we denote by  $\lambda_{\gamma_1, \gamma_2}$  the canonical unitaries in the two crossed products and by the same  $\theta$  the dual action on  $\widehat{G}^2 \ltimes \widehat{M}$  and  $\widehat{G}^2 \ltimes \widehat{M}_\Omega$ . Recall that  $\theta$  and  $\lambda$  verify

$$\theta_{g_1, g_2}(\lambda_{\gamma_1, \gamma_2}) = \overline{\langle \gamma_1, g_1 \rangle \langle \gamma_2, g_2 \rangle} \lambda_{\gamma_1, \gamma_2}.$$

The unitary representations  $\gamma \mapsto \lambda_{(\gamma, 0)}$ ,  $\gamma \mapsto \lambda_{(0, \gamma)}$  and  $\lambda$  give unital normal \*-homomorphisms  $\lambda_L, \lambda_R : L^\infty(G) \rightarrow \widehat{G}^2 \ltimes \widehat{M}$  and  $\lambda : L^\infty(G^2) \rightarrow \widehat{G}^2 \ltimes \widehat{M}$  verifying

$$\lambda_L(u_\gamma) = \lambda_{(\gamma, 0)}, \quad \lambda_R(u_\gamma) = \lambda_{(0, \gamma)}, \quad \lambda(u_{(\gamma_1, \gamma_2)}) = \lambda_{\gamma_1, \gamma_2}.$$

Since  $\lambda(f_1 \otimes f_2) = \lambda_L(f_1)\lambda_R(f_2)$ , then

$$\begin{aligned} \theta_{(g_1, g_2)}(\lambda_L(F)) &= \lambda_L(F(\cdot - g_1)), \quad \text{for any } F \in L^\infty(G). \\ \theta_{(g_1, g_2)}(\lambda_R(F)) &= \lambda_R(F(\cdot - g_2)), \quad \text{for any } F \in L^\infty(G). \end{aligned} \tag{9}$$

We have for the twisted dual action  $\theta^\Psi$ :

$$\theta_{(g_1, g_2)}^\Psi(\pi(x)) = \pi(\alpha_{(\Psi_{-g_1}, \Psi_{g_2})}(x)), \quad \text{for all } x \in \widehat{M}. \tag{10}$$

Considering the following unitaries in  $M \otimes N$ :

$$\tilde{X} = (\alpha \otimes \lambda_L)(\Psi^*), \tilde{Y} = (\alpha \otimes \lambda_R)(\tilde{\Psi}) = (\alpha(u) \otimes 1)(\alpha \otimes \lambda_R)(\Psi^*), \tilde{W} = (\iota \otimes \pi)(W),$$

we put  $\tilde{W}_\Omega = \tilde{Y}\tilde{W}\tilde{X}$ . Let  $N_\Omega$  be the fixed point subalgebra of  $\widehat{G}^2 \times \widehat{M}$  under the twisted dual action. The step to prove Theorem 2 is to show that  $\widehat{M}_\Omega$  is isomorphic to  $N_\Omega$ , for this we need a preliminary lemma. Let  $\mathcal{B}$  be the von Neumann algebra acting on  $H$  and generated by  $\{(\omega \otimes \iota)(W\Omega^*) \mid \omega \in \mathcal{B}(H)_*\}$ .

**Lemma 7** *We have:*

- $\mathcal{B} \vee \{L_\gamma \mid \gamma \in \widehat{G}\}'' = \widehat{M} \vee \{L_\gamma \mid \gamma \in \widehat{G}\}''$ ,
- $\mathcal{B} \vee \{R_\gamma \mid \gamma \in \widehat{G}\}'' = \widehat{M}_\Omega \vee \{R_\gamma \mid \gamma \in \widehat{G}\}''$ .

**Proof.** First, take a net in the vector space spanned by elements  $u_{\gamma_1} \otimes u_{\gamma_2}$  such that  $\sum c_{i,j} u_{\gamma_i, \gamma_j} \rightarrow \Psi$  strongly\*. Then  $(\omega \otimes \iota)(W\Omega^*)$  is the weak limit of  $\sum \overline{c_{i,j}} (L_{-\gamma_i} \cdot \omega \otimes \iota)(W) L_{-\gamma_j}$ , so  $\mathcal{B} \subset \widehat{M} \vee \{L_\gamma \mid \gamma \in \widehat{G}\}''$ . For the converse inclusion note that  $(\omega \otimes \iota)(W) = (\omega \otimes \iota)(W\Omega^*\Omega)$ . Thus,  $(\omega \otimes \iota)(W)$  is the weak limit of  $\sum c_{i,j} (L_{\gamma_i} \cdot \omega \otimes \iota)(W\Omega^*) L_{\gamma_j}$ . The second assertion can be proved using the same technique.  $\blacksquare$

**Proposition 5** *There exists a \*-isomorphism  $\rho : \widehat{G}^2 \times \widehat{M} \rightarrow \widehat{G}^2 \times \widehat{M}_\Omega$  intertwining the actions  $\theta^\Psi$  on  $\widehat{G}^2 \times \widehat{M}$  and  $\theta$  on  $\widehat{G}^2 \times \widehat{M}_\Omega$ . Moreover,*

$$\rho((\omega \otimes \iota)(\tilde{W}_\Omega)) = \pi((\omega \otimes \iota)(W_\Omega)).$$

**Proof.** Remark that if we put  $V = (\mathcal{F} \otimes \mathcal{F})U$  where  $\mathcal{F} : \rightarrow L^2(G)$  is the Fourier transform and  $U : L^2(\widehat{G} \times \widehat{G}) \otimes H \rightarrow L^2(\widehat{G} \times \widehat{G}) \otimes H$  is the unitary defined by  $(U\xi)(\gamma_1, \gamma_2) = L_{\gamma_1} R_{\gamma_2} \xi(\gamma_1, \gamma_2)$  then

$$\begin{cases} V\pi(x)V^* &= 1 \otimes 1 \otimes x, \\ V\lambda_{\gamma,0}V^* &= u_\gamma \otimes 1 \otimes L_\gamma, \\ V\lambda_{0,\gamma}V^* &= 1 \otimes u_\gamma \otimes R_\gamma. \end{cases}$$

Applying  $\alpha \otimes \alpha \otimes \iota$ , we conclude that the crossed products can be defined on  $H \otimes H \otimes H$  by:

$$\begin{aligned} \widehat{G}^2 \times \widehat{M} &= \{L_\gamma \otimes 1 \otimes L_\gamma \mid \gamma \in \widehat{G}\}'' \vee \{1 \otimes L_\gamma \otimes R_\gamma \mid \gamma \in \widehat{G}\}'' \vee 1 \otimes 1 \otimes \widehat{M}, \\ \widehat{G}^2 \times \widehat{M}_\Omega &= \{L_\gamma \otimes 1 \otimes L_\gamma \mid \gamma \in \widehat{G}\}'' \vee \{1 \otimes L_\gamma \otimes R_\gamma \mid \gamma \in \widehat{G}\}'' \vee 1 \otimes 1 \otimes \widehat{M}_\Omega. \end{aligned}$$

Put  $\mathcal{W} = (\widehat{J} \otimes \widehat{J})W(\widehat{J} \otimes \widehat{J})$ . Then  $\mathcal{W}^*(1 \otimes x)\mathcal{W} = \Delta^{\text{op}}(x)$ , for all  $x \in M$  and  $[\mathcal{W}, 1 \otimes y] = 0$ , for all  $y \in \widehat{M}$ . We have also  $\mathcal{W}_\Omega = (\widehat{J}_\Omega \otimes \widehat{J}_\Omega)W\Omega(\widehat{J}_\Omega \otimes \widehat{J}_\Omega)$  with similar properties.

In the following computation we use the relations  $\mathcal{W}^*(1 \otimes L_\gamma)\mathcal{W} = L_\gamma \otimes L_\gamma$ ,  $\mathcal{W}(1 \otimes R_\gamma)\mathcal{W}^* = L_\gamma \otimes R_\gamma$  and similar relations with  $\mathcal{W}_\Omega$ . We use also the equality

$[\mathcal{W}_{13}\Omega_{31}^*, \mathcal{W}_{23}\Omega_{23}^*] = 0$  implying  $[\mathcal{W}\Omega_{21}^*, 1 \otimes y] = 0$ , for all  $y \in \mathcal{B}$ . Finally, using Lemma 7, we have:

$$\begin{aligned}
\widehat{G}^2 \times \widehat{M} &= \{L_\gamma \otimes 1 \otimes L_\gamma \mid \gamma \in \widehat{G}\}'' \vee \{1 \otimes L_\gamma \otimes R_\gamma \mid \gamma \in \widehat{G}\}'' \vee 1 \otimes 1 \otimes \widehat{M} \\
&\quad \downarrow \text{Ad}(\mathcal{W}_{13}) \\
&= \{1 \otimes 1 \otimes L_\gamma\}'' \vee \{L_\gamma \otimes L_\gamma \otimes R_\gamma\}'' \vee 1 \otimes 1 \otimes \widehat{M} \\
&= \{1 \otimes 1 \otimes L_\gamma\}'' \vee \{L_\gamma \otimes L_\gamma \otimes R_\gamma\}'' \vee 1 \otimes 1 \otimes \widehat{B} \quad := L_1 \\
&\quad \downarrow \text{Ad}(\Omega_{32}\mathcal{W}_{23}^*\Omega_{31}\mathcal{W}_{13}^*) \\
&= \{L_\gamma \otimes L_\gamma \otimes L_\gamma\}'' \vee \{1 \otimes 1 \otimes R_\gamma\}'' \vee 1 \otimes 1 \otimes \widehat{B} \\
&= \{L_\gamma \otimes L_\gamma \otimes L_\gamma\}'' \vee \{1 \otimes 1 \otimes R_\gamma\}'' \vee 1 \otimes 1 \otimes \widehat{M}_\Omega \quad := L_2 \\
&\quad \downarrow \text{Ad}((\mathcal{W}_\Omega)_{23}) \\
\{L_\gamma \otimes 1 \otimes L_\gamma \mid \gamma \in \widehat{G}\}'' \vee \{1 \otimes L_\gamma \otimes R_\gamma \mid \gamma \in \widehat{G}\}'' \vee 1 \otimes 1 \otimes \widehat{M}_\Omega &= \widehat{G}^2 \times \widehat{M}_\Omega.
\end{aligned}$$

Define  $\rho := \rho_2 \circ \Phi \circ \rho_1$ , where  $\rho_1$ ,  $\Phi$  and  $\rho_2$  are the isomorphisms from  $\widehat{G}^2 \times \widehat{M}$  to  $L_1$ , from  $L_1$  to  $L_2$ , and from  $L_2$  to  $\widehat{G}^2 \times \widehat{M}_\Omega$ , respectively. Then one can check that  $\rho \circ \theta_{g_1, g_2}^\Psi(x) = \theta_{g_1, g_2} \circ \rho(x)$ , for all  $g_1, g_2 \in G$  and for all  $x$  of the form  $\lambda_{\gamma_1, \gamma_2}$  (or  $L_\gamma \otimes 1 \otimes L_\gamma$  and  $1 \otimes L_\gamma \otimes R_\gamma$  in our description of the crossed products). Thus, to finish the proof we only have to show that  $(\omega \otimes \iota)(\tilde{W}_\Omega) \in N_\Omega$  and  $\rho((\omega \otimes \iota)(\tilde{W}_\Omega)) = \pi((\omega \otimes \iota)(W_\Omega))$ . Using (9), one computes

$$\begin{aligned}
(\iota \otimes \theta_{(g_1, g_2)}^\Psi)(\tilde{X}) &= (\iota \otimes \theta_{(g_1, g_2)})(\tilde{X}) = (\alpha \otimes \lambda_L)(\Psi^*(\cdot, \cdot - g_1)) \\
&= (\alpha \otimes \lambda_L)(\Psi_{g_1} \otimes 1)(\alpha \otimes \lambda_L)(\Psi^*) \\
&= (\alpha(\Psi_{g_1}) \otimes 1)\tilde{X}.
\end{aligned} \tag{11}$$

Similarly

$$\begin{aligned}
(\iota \otimes \theta_{(g_1, g_2)}^\Psi)(\tilde{Y}) &= (\iota \otimes \theta_{(g_1, g_2)})(\tilde{Y}) = (\iota \otimes \theta_{(g_1, g_2)})((\alpha \otimes \lambda_R)(\tilde{\Psi})) \\
&= (\alpha \otimes \lambda_R)(\tilde{\Psi}(\cdot, \cdot - g_2)) = \tilde{Y}(\alpha(\Psi_{g_2}) \otimes 1).
\end{aligned} \tag{12}$$

And, using (10) and (4), one has

$$\begin{aligned}
(\iota \otimes \theta_{(g_1, g_2)}^\Psi)(\tilde{W}) &= (\iota \otimes \pi)((L_{\Psi_{-g_2}} \otimes 1)W(L_{\Psi_{-g_1}} \otimes 1)) \\
&= (\alpha(\Psi_{g_2}^*) \otimes 1)\tilde{W}(\alpha(\Psi_{g_1}^*) \otimes 1).
\end{aligned} \tag{13}$$

Now (11), (12), and (13) imply  $(\iota \otimes \theta_{(g_1, g_2)}^\Psi)(\tilde{W}_\Omega) = \tilde{W}_\Omega$ , so  $(\omega \otimes \iota)(\tilde{W}_\Omega) \in N_\Omega$ . Now we want to show that  $\rho((\omega \otimes \iota)(\tilde{W}_\Omega)) = \pi((\omega \otimes \iota)(W_\Omega))$ . We take a net in the vector space spanned by elements  $u_{\gamma_1} \otimes u_{\gamma_2}$  such that  $\sum c_{i,j}(u_{\gamma_i} \otimes u_{\gamma_j}) \rightarrow \Psi$  strongly\*, so  $\sum \bar{c}_{i,j}(L_{-\gamma_i} \otimes \lambda_{-\gamma_j, 0}) \rightarrow \tilde{X}$  and  $\sum \bar{c}_{i,j}(\alpha(u) \otimes 1)(L_{-\gamma_i} \otimes \lambda_{0, -\gamma_j}) \rightarrow \tilde{Y}$  strongly\*. This implies

$$\sum \bar{c}_{i,j} \bar{c}_{k,l} \lambda_{0, -\gamma_j} \pi((L_{-\gamma_k} \cdot \omega \cdot L_{-\gamma_i} \cdot \alpha(u) \otimes \iota)(W)) \lambda_{-\gamma_i, 0} \rightarrow (\omega \otimes \iota)(\tilde{W}_\Omega) \quad \text{weakly.}$$

Thus  $\rho_1((\omega \otimes \iota)(\tilde{W}_\Omega))$  is the weak limit of the net

$$\begin{aligned} & \sum \bar{c}_{i,j} \bar{c}_{k,l} (L_{-\gamma_j} \otimes L_{-\gamma_j} \otimes R_{-\gamma_j}) (1 \otimes 1 \otimes (L_{-\gamma_k} \cdot \omega \cdot L_{-\gamma_i} \cdot \alpha(u) \otimes \iota)(W)) (1 \otimes 1 \otimes L_{-\gamma_l}) \\ &= \sum_{i,j} \bar{c}_{i,j} (L_{-\gamma_j} \otimes L_{-\gamma_j} \otimes R_{-\gamma_j}) (1 \otimes 1 \otimes (\omega \cdot L_{-\gamma_i} \cdot \alpha(u) \otimes \iota)(W \sum_{k,l} \bar{c}_{k,l} L_{-\gamma_k} \otimes L_{-\gamma_l})) \\ &\longrightarrow_{k,l} \sum_{i,j} \bar{c}_{i,j} (L_{-\gamma_j} \otimes L_{-\gamma_j} \otimes R_{-\gamma_j}) (1 \otimes 1 \otimes (\omega \cdot L_{-\gamma_i} \cdot \alpha(u) \otimes \iota)(W\Omega^*)). \end{aligned}$$

and  $\Phi \circ \rho_1((\omega \otimes \iota)(\tilde{W}_\Omega))$  is the weak limit of the net

$$\begin{aligned} & \sum \bar{c}_{i,j} (1 \otimes 1 \otimes R_{0,-\gamma_j}) (1 \otimes 1 \otimes (\omega \cdot L_{-\gamma_i} \cdot \alpha(u) \otimes \iota)(W\Omega^*)) \\ &= 1 \otimes 1 \otimes (\omega \otimes \iota) \left( \sum \bar{c}_{i,j} (\alpha(u) \otimes 1) (L_{-\gamma_i} \otimes R_{-\gamma_j}) W\Omega^* \right). \end{aligned}$$

Because  $\sum \bar{c}_{i,j} (\alpha(u) \otimes 1) (L_{-\gamma_i} \otimes R_{-\gamma_j}) \rightarrow Y$  weakly, we have

$$\Phi \circ \rho_1((\omega \otimes \iota)(\tilde{W}_\Omega)) = 1 \otimes 1 \otimes (\omega \otimes \iota)(W_\Omega).$$

This concludes the proof.  $\blacksquare$

In particular, Proposition 5 implies that  $N_\Omega = \{(\omega \otimes \iota)(\tilde{W}_\Omega) \mid \omega \in \mathcal{B}(H)_*\}$  and that  $\rho$  is a \*-isomorphism from  $N_\Omega$  to  $\widehat{M}_\Omega$  which sends  $(\omega \otimes \iota)(\tilde{W}_\Omega)$  to  $(\omega \otimes \iota)(W_\Omega)$ . Thus, we can transport the l.c. quantum group structure from  $\widehat{M}_\Omega$  to  $N_\Omega$ . First, we show that the comultiplication introduced in Section 2.7 is the good one. For this we need

**Proposition 6** *There exists a unique unital normal \*-homomorphism  $\Gamma : N \rightarrow N \otimes N$  such that*

$$\Gamma(\lambda_{\gamma_1, \gamma_2}) = \lambda_{\gamma_1, 0} \otimes \lambda_{0, \gamma_2} \quad \text{and} \quad \Gamma(\pi(x)) = (\pi \otimes \pi) \hat{\Delta}(x).$$

**Proof.** Like in the begining of the proof of Proposition 5 define the crossed product

$$\widehat{G}^2 \rtimes \widehat{M} = \{L_\gamma \otimes 1 \otimes L_\gamma \mid \gamma \in \widehat{G}\}'' \vee \{1 \otimes L_\gamma \otimes R_\gamma \mid \gamma \in \widehat{G}\}'' \vee 1 \otimes 1 \otimes \widehat{M}.$$

Let  $\mathcal{W}$  be the operator defined in the proof of Proposition 5 and  $Q$  be the unitary on  $H \otimes H \otimes H \otimes H \otimes H \otimes H$  such that  $Q^* = \Sigma_{45} \Sigma_{35} \mathcal{W}_{15}^* \widehat{W}_{56}^* \Sigma_{45}$ . We define  $\Gamma(x) = Q^*(1 \otimes x)Q$ . Using that  $\widehat{W}^*(L_\gamma \otimes L_\gamma) \widehat{W} = L_\gamma \otimes 1$ ,  $\hat{\Delta}(x) = \widehat{W}^*(1 \otimes x) \widehat{W}$ , for all  $x \in \hat{M}$ ,  $[\widehat{W}, 1 \otimes y] = 0$ , for all  $y \in \hat{M}'$ ,  $\mathcal{W}^*(1 \otimes L_\gamma) \mathcal{W} = L_\gamma \otimes L_\gamma$  and  $[\mathcal{W}, 1 \otimes y] = 0$ , for all  $y \in \hat{M}$ , one can check that the needed properties of  $\Gamma$ .  $\blacksquare$

The unitary  $\Upsilon = (\lambda_R \otimes \lambda_L)(\tilde{\Psi}^*) \in N \otimes N$  allows to define the unital normal \*-homomorphism  $\Gamma_\Omega(x) = \Upsilon \Gamma(x) \Upsilon^* : N \rightarrow N \otimes N$  which is a comultiplication on  $N_\Omega$ :

**Proposition 7** *For all  $x \in N_\Omega$ , we have  $\Gamma_\Omega(x) \in N_\Omega \otimes N_\Omega$  and*

$$(\rho \otimes \rho)(\Gamma_\Omega(x)) = \hat{\Delta}_\Omega(\rho(x)).$$

**Proof.** It suffices to show that  $(\iota \otimes \rho \otimes \rho)(\iota \otimes \Gamma_\Omega)(\tilde{W}_\Omega) = (W_\Omega)_{13}(W_\Omega)_{12}$ . By the definition of  $\Gamma$ , one has, for any  $F \in L^\infty(G)$ ,

$$\Gamma(\lambda_L(F)) = \lambda_L(F) \otimes 1 \quad \text{and} \quad \Gamma(\lambda_R(F)) = 1 \otimes \lambda_R(F),$$

and since  $1 \otimes \Upsilon$  commutes with  $\tilde{X}_{12}$  and with  $\tilde{Y}_{13}$ , one gets:

$$(\iota \otimes \Gamma_\Omega)(\tilde{X}) = \tilde{X}_{12} \quad \text{and} \quad (\iota \otimes \Gamma_\Omega)(\tilde{Y}) = \tilde{Y}_{13}.$$

Moreover,

$$\begin{aligned} (\iota \otimes \Gamma_\Omega)(\tilde{W}) &= (1 \otimes \Upsilon)(\iota \otimes \Gamma \circ \pi)(W)(1 \otimes \Upsilon^*) \\ &= (1 \otimes \Upsilon)(\iota \otimes \pi \otimes \pi) \left( (\iota \otimes \hat{\Delta})(W) \right) (1 \otimes \Upsilon^*) \\ &= (1 \otimes \Upsilon)(\iota \otimes \pi \otimes \pi)(W_{13}W_{12})(1 \otimes \Upsilon^*) \\ &= \Upsilon_{23}\tilde{W}_{13}\tilde{W}_{12}\Upsilon_{23}^*. \end{aligned}$$

Using (3), we can check the following relations on the generators  $u_\gamma$  of  $L^\infty(G)$ :

$$\begin{aligned} W(1 \otimes \pi_R(F))W^* &= (\pi_L \otimes \pi_R)(\Delta_G(F)), \\ W^*(1 \otimes \pi_L(F))W &= (\pi_L \otimes \pi_L)(\Delta_G(F)), \text{ for any } F \in L^\infty(G). \end{aligned}$$

Then

$$\begin{aligned} W_{12}(\pi_R \otimes \pi_L)(\tilde{\Psi}^*)_{23}W_{12}^* &= (\pi_L \otimes \pi_R \otimes \pi_L) \left( (\Delta_G \otimes \iota)(\tilde{\Psi}) \right), \\ W_{13}^*(\pi_R \otimes \pi_L)(\tilde{\Psi}^*)_{23}W_{13} &= (\pi_L \otimes \pi_R \otimes \pi_L) \left( (\sigma \otimes \iota) \left( (\iota \otimes \Delta_G)(\tilde{\Psi}^*) \right) \right). \end{aligned}$$

Let us define

$$V = (\pi_L \otimes \pi_R \otimes \pi_L) \left( (\sigma \otimes \iota) \left( (\iota \otimes \Delta_G)(\tilde{\Psi}^*) \right) \right) (\pi_L \otimes \pi_R \otimes \pi_L) \left( (\Delta_G \otimes \iota)(\tilde{\Psi}) \right),$$

then we have

$$\begin{aligned} (\iota \otimes \rho \otimes \rho)(\iota \otimes \Gamma_\Omega)(\tilde{W}_\Omega) &= (\iota \otimes \rho \otimes \rho)(\tilde{Y}_{13}\Upsilon_{23}\tilde{W}_{13}\tilde{W}_{12}\Upsilon_{23}^*\tilde{X}_{12}) \\ &= Y_{13}W_{13}VW_{12}X_{12}, \end{aligned}$$

so it remains to calculate:

$$\begin{aligned} &(\sigma \otimes \iota) \left( (\iota \otimes \Delta_G)(\tilde{\Psi}^*) \right) (g, h, t)(\Delta_G \otimes \iota)(\tilde{\Psi})(g, h, t) \\ &= (\iota \otimes \Delta_G)(\tilde{\Psi}^*)(h, g, t)(\Delta_G \otimes \iota)(\tilde{\Psi})(g, h, t) \\ &= \Psi^*(-h, h + g + t)\Psi(-g - h, g + h + t) = \Psi(-g, g + h + t) \\ &= \Psi^*(g, t)\tilde{\Psi}(g, h). \end{aligned}$$

Thus,  $V = X_{13}Y_{12}$ , and this concludes the proof. ■

**Remark.** One can show that  $\alpha$  and  $\beta$  are actions of  $\widehat{G}^2$  on the reduced dual  $C^*$ -algebras  $\widehat{A}$  and  $\widehat{A}_\Omega$ . Moreover, the  $*$ -isomorphism  $\rho$  gives a  $*$ -isomorphism between the reduced crossed products  $\widehat{G}^2 \ltimes \widehat{A}$  and  $\widehat{G}^2 \ltimes \widehat{A}_\Omega$ . So  $\widehat{A}$  is nuclear if and only if  $\widehat{A}_\Omega$  is nuclear. Moreover, the twisted dual action  $\theta^\Psi$  gives a deformed  $\widehat{G}^2$ -product structure on  $\widehat{G}^2 \ltimes \widehat{A}$  and the Landstad algebra for this  $\widehat{G}^2$ -product is  $[(\omega \otimes \iota)(\widehat{W}_\Omega)]$ , and it is isomorphic to  $\widehat{A}_\Omega$ . These results can be obtained directly from the universality property of crossed products (see [4]).

The rest of this section is devoted to the computation of the left invariant weight on  $(N_\Omega, \Gamma_\Omega)$ . Since  $\rho : N = \widehat{G}^2 \ltimes \widehat{M} \rightarrow \widehat{G}^2 \ltimes \widehat{M}_\Omega$  is a  $*$ -isomorphism, one can consider two natural weights on  $N$ ,  $\varphi_1 = \widehat{\varphi}$ , the dual weight of  $\widehat{\varphi}$  on  $N$ , and  $\varphi_2 = \widehat{\varphi}_\Omega \circ \rho$ , where  $\widehat{\varphi}_\Omega$  is the dual weight of  $\widehat{\varphi}_\Omega$  on  $\widehat{G}^2 \ltimes \widehat{M}_\Omega$ .

**Lemma 8** *We have:*

1.  $[D\widehat{\varphi} \circ \alpha_{\gamma_1, \gamma_2} : D\widehat{\varphi}]_t = \langle \gamma_2, \gamma_t \rangle = [D\widehat{\varphi}_\Omega \circ \beta_{\gamma_1, \gamma_2} : D\widehat{\varphi}_\Omega]_t \quad \forall t \in \mathbb{R}, \forall \gamma_1, \gamma_2 \in \widehat{G}$ .
2.  $[D\varphi_1 \circ \theta_{g_1, g_2}^\Psi : D\varphi_1]_t = \Psi(\gamma_t, g_2)$ , for all  $t \in \mathbb{R}$  and all  $g_1, g_2 \in G$ .
3. For any n.s.f. weight  $\nu$  on  $N$ ,  $\nu$  is invariant under the action  $\theta^\Psi$  if and only if  $\theta_{g_1, g_2}^\Psi([D\nu : D\varphi_1]_t) = \Psi(\gamma_t, g_2)[D\nu : D\varphi_1]_t$ .

**Proof.** Using Proposition 3(2), and because  $L_\gamma$  and  $R_\gamma$  are unitaries, we find  $\widehat{\varphi} \circ \alpha_\gamma^L = \widehat{\varphi}$ ,  $\widehat{\varphi} \circ \alpha_\gamma^R = \lambda(\gamma)\widehat{\varphi}$ , so

$$\begin{aligned} [D\widehat{\varphi} \circ \alpha_{\gamma_1, \gamma_2} : D\widehat{\varphi}]_t &= [D\widehat{\varphi} \circ \alpha_{\gamma_1}^L \circ \alpha_{\gamma_2}^R : D\widehat{\varphi} \circ \alpha_{\gamma_2}^R]_t [D\widehat{\varphi} \circ \alpha_{\gamma_2}^R : D\widehat{\varphi}]_t \\ &= \alpha_{-\gamma_2}^R ([D\widehat{\varphi} \circ \alpha_{\gamma_1}^L : D\widehat{\varphi}]_t) [D\widehat{\varphi} \circ \alpha_{\gamma_2}^R : D\widehat{\varphi}]_t \\ &= \lambda(\gamma_2)^{it} = \langle \gamma_2, \gamma_t \rangle. \end{aligned}$$

The right-hand side of the first equality is obtained by considering the stable co-subgroup  $\widehat{G} < (M, \Delta_\Omega)$ . Let us prove the second assertion. Let  $g_1, g_2 \in G$ , define the unitary  $v := \lambda_{(\Psi_{-g_1}, \Psi_{g_2})}$ , and denote by  $\varphi_1|_v$  the weight  $\varphi_1|_v(x) = \varphi_1(vxv^*)$ . Using the first assertion, we have

$$[D\varphi_1|_v : D\varphi_1]_t = v^* \sigma_t^1(v) = v^* \langle \Psi_{g_2}, \gamma_t \rangle v = \Psi(\gamma_t, g_2).$$

Note that  $\varphi_1 \circ \theta_{g_1, g_2}^\Psi = \varphi_1|_v \circ \theta_{g_1, g_2}$ , so

$$\begin{aligned} [D\varphi_1 \circ \theta_{g_1, g_2}^\Psi : D\varphi_1]_t &= [D\varphi_1|_v \circ \theta_{g_1, g_2} : D\varphi_1 \circ \theta_{g_1, g_2}]_t [D\varphi_1 \circ \theta_{g_1, g_2} : D\varphi_1]_t \\ &= \theta_{-g_1, -g_2}([D\varphi_1|_v : D\varphi_1]_t) = \Psi(\gamma_t, g_2). \end{aligned}$$

Putting  $u_t = [D\nu : D\varphi_1]_t$  and using the second assertion, one has

$$[D\nu \circ \theta_{g_1, g_2}^\Psi : D\nu]_t = \theta_{-g_1, -g_2}^\Psi(u_t) [D\varphi_1 \circ \theta_{g_1, g_2}^\Psi : D\varphi_1]_t u_t^* = \theta_{-g_1, -g_2}^\Psi(u_t) \Psi(\gamma_t, g_2) u_t^*.$$

This concludes the proof.  $\blacksquare$

Note that, using Lemma 8 (1), we have, for all  $t \in \mathbb{R}, F \in L^\infty(G^2)$ ,

$$\sigma_t^1(\lambda(F)) = \lambda(F(\cdot, \cdot + \gamma_t)) = \sigma_t^2(\lambda(F)). \quad (14)$$

Let  $T$  be the strictly positive operator affiliated with  $N$  and such that  $T^{it} = \lambda_R(\Psi(-\gamma_t, \cdot))$ . Using (14), we find  $\sigma_t^1(T^{is}) = \lambda^{-its}T^{is}$ , so one can consider the Vaes' weight  $\tilde{\mu}_\Omega$  associated with  $T$  and  $\lambda^{-1}$ . This is the unique n.s.f. weight on  $N$  such that  $[D\tilde{\mu}_\Omega : D\varphi_1]_t = \lambda^{-\frac{it^2}{2}}T^{it}$ . From (9) we have  $\theta_{g_1, g_2}^\Psi(T^{it}) = \lambda_R(\Psi(-\gamma_t, \cdot - g_2)) = \Psi(\gamma_t, g_2)T^{it}$ . By Lemma 8(3),  $\tilde{\mu}_\Omega$  is invariant under  $\theta^\Psi$ , so the image  $\tilde{\mu}_\Omega \circ \rho^{-1}$  of  $\tilde{\mu}_\Omega$  in  $\hat{G}^2 \times \hat{M}_\Omega$  is invariant under the dual action. Thus,  $\tilde{\mu}_\Omega \circ \rho^{-1}$  is the dual weight of some weight  $\mu_\Omega$  on  $\hat{M}_\Omega$ . To finish the proof of Theorem 2, we will show in Theorem 6 that  $\mu_\Omega = \hat{\varphi}_\Omega$ , for which we need

**Proposition 8** *For all  $t \in \mathbb{R}$  and all  $x \in N$ , we have*

$$\sigma_t^2(x) = T^{it}\sigma_t^1(x)T^{-it}.$$

**Proof.** By (14), it suffices to prove this equality for elements of the form  $(\omega \otimes \iota)(\tilde{W}_\Omega)$ . By definition of  $\sigma_t^2$ , we have

$$\sigma_t^2\left((\omega \otimes \iota)(\tilde{W}_\Omega)\right) = (\rho_t^\Omega(\omega) \otimes \iota)(\tilde{W}_\Omega),$$

where  $\rho_t^\Omega(\omega)(x) = \omega(\delta_\Omega^{-it}\tau_{-t}^\Omega(x))$ . Proposition 4 gives

$$\rho_t^\Omega(x) = \omega(\delta^{-it}A^{it}B^{-it}\tau_t(x)).$$

On the other hand, using (14), one has

$$(\iota \otimes \sigma_t^1)(\tilde{X}) = \tilde{X}, \quad (\iota \otimes \sigma_t^2)(\tilde{Y}) = (A^{it} \otimes 1)\tilde{Y},$$

which implies

$$\begin{aligned} (\iota \otimes \sigma_t^1)(\tilde{W}_\Omega) &= (A^{it} \otimes 1)\tilde{Y}(\rho_t(\omega) \otimes \iota)(\tilde{W})\tilde{X} \\ &= (A^{it} \otimes 1)\tilde{Y}(\delta^{-it} \otimes 1)(\tau_{-t} \otimes \iota)(\tilde{W})\tilde{X} \\ &= (B^{it} \otimes 1)(\delta^{-it}A^{it}B^{-it} \otimes 1)(\tau_{-t} \otimes \iota)(\tilde{W}_\Omega) \\ &\quad \text{because } \delta^{it}\alpha(\cdot)\delta^{-it} = \alpha(\cdot) \text{ and } \tau_t \circ \alpha = \tau_t \\ &= (B^{it} \otimes 1)(\iota \otimes \sigma_t^2)(\tilde{W}_\Omega). \end{aligned}$$

Next, using (3) with the character  $\chi_t(g) = \Psi(\gamma_t, g)$ , we find

$$\begin{aligned} (B^{it} \otimes 1)\tilde{W}_\Omega &= \tilde{Y}(L_{-\chi_t} \otimes 1)\tilde{W}\tilde{X} = \tilde{Y}(\iota \otimes \pi)((L_{-\chi_t} \otimes 1)W)\tilde{X} \\ &= \tilde{Y}(\iota \otimes \pi)((1 \otimes R_{\chi_t})W(1 \otimes R_{\chi_t}^*))\tilde{X} = (1 \otimes \lambda_R(\chi_t))\tilde{W}_\Omega(1 \otimes \lambda_R(\chi_t)^*) \\ &= (1 \otimes T^{-it})\tilde{W}_\Omega(1 \otimes T^{it}). \end{aligned} \tag{15}$$

Thus, for all  $t \in \mathbb{R}, \omega \in M_*$ , one has

$$\begin{aligned} \sigma_t^1((\omega \otimes \iota)(\tilde{W}_\Omega)) &= (\omega \otimes \iota)((B^{it} \otimes 1)(\iota \otimes \sigma_t^2)(\tilde{W}_\Omega)) \\ &= (\omega \otimes \iota)((\iota \otimes \sigma_t^2)((1 \otimes T^{-it})\tilde{W}_\Omega(1 \otimes T^{it}))) \\ &= T^{-it}\sigma_t^2((\omega \otimes \iota)(\tilde{W}_\Omega))T^{it}, \end{aligned}$$

where we used, in the last equation,  $\sigma_t^2(T^{is}) = \lambda^{-ist}T^{is}$ . ■

**Theorem 6** *We have  $\mu_\Omega = \hat{\varphi}_\Omega$ .*

Let us denote by  $\varphi_P$  the Plancherel weight on  $\mathcal{L}(\hat{G}^2)$ , by  $\Lambda_P$  its canonical G.N.S. map, by  $\lambda_L^{\hat{G}^2}$  and  $\lambda_R^{\hat{G}^2}$  the  $*$ -homomorphisms  $L^\infty(G) \rightarrow \mathcal{L}(\hat{G}^2)$  coming from the representations  $(\gamma \mapsto \lambda_{(\gamma,0)}^{\hat{G}^2})$  and  $(\gamma \mapsto \lambda_{(0,\gamma)}^{\hat{G}^2})$ , respectively, and by  $T_1^{it} = \lambda_R^{\hat{G}^2}(\Psi(-\gamma_t, \cdot))$ . Thus,  $T = T_1 \otimes 1$ . We also introduce the  $*$ -homomorphism  $\alpha'(F) = J\alpha(F)^*J$  and denote by  $F \mapsto F^\circ$  the  $*$ -automorphism of  $L^\infty(G \times G)$  defined by  $F^\circ(g, h) = F(h, g + h)$ .

The standard G.N.S. construction for  $\varphi_1$  is  $(L^2(\hat{G}^2, H), \iota, \Lambda_1)$ , where a  $\sigma$ -strong- $*$ -norm core for  $\Lambda_1$  is given by

$$\mathcal{D}_1 = \left\{ (x \otimes 1)(\omega \otimes \iota)(\tilde{W}) \mid x \in \mathcal{N}_{\varphi_P}, \omega \in \mathcal{I} \right\},$$

and, if  $x \in \mathcal{N}_{\varphi_P}$ ,  $\omega \in \mathcal{I}$ , we have

$$\Lambda_1 \left( (x \otimes 1)(\omega \otimes \iota)(\tilde{W}) \right) = \Lambda_P(x) \otimes \xi(\omega).$$

Let  $\lambda_\Omega(\omega)$ ,  $\mathcal{I}_\Omega$ , and  $\xi_\Omega$  be the standard objects associated with  $(M, \Delta_\Omega)$ . For  $\varphi_2$ , we take the G.N.S. construction  $(L^2(\hat{G}^2, H), \tilde{\rho}, \Lambda_2)$ , where a  $\sigma$ -strong- $*$ -norm core for  $\Lambda_2$  is

$$\mathcal{D}_2 = \left\{ (x \otimes 1)(\omega \otimes \iota)(\tilde{W}_\Omega) \mid x \in \mathcal{N}_{\varphi_P}, \omega \in \mathcal{I}_\Omega \right\},$$

and, if  $x \in \mathcal{N}_{\varphi_P}$ ,  $\omega \in \mathcal{I}_\Omega$ , one has

$$\Lambda_2 \left( (x \otimes 1)(\omega \otimes \iota)(\tilde{W}_\Omega) \right) = \Lambda_P(x) \otimes \xi_\Omega(\omega).$$

Let us introduce the following sets:

$$\begin{aligned} C_1 &= \left\{ x \in \mathcal{N}_{\varphi_P} \mid T^{\frac{1}{2}}(x \otimes 1) \text{ is bounded} \right\}, \\ C_1^0 &= \left\{ x \in C_1 \mid \Lambda_P(x) \in \mathcal{D}(T_1^{-\frac{1}{2}}) \right\}, \\ C_2 &= \left\{ \omega_{\xi, \eta} \in \mathcal{I}_\Omega \mid \eta \in \mathcal{D}(A^{-\frac{1}{2}}) \cap \mathcal{D}(B^{\frac{1}{2}}) \right\}. \end{aligned}$$

**Lemma 9** *For all  $\omega_{\xi, \eta} \in C_2$  one has  $\omega_{\xi, A^{-\frac{1}{2}}\eta}, \omega_{\xi, u^* B^{\frac{1}{2}}\eta} \in \mathcal{I}$ . Moreover,*

$$\xi_\Omega(\omega_{\xi, \eta}) = \xi \left( \omega_{\xi, A^{-\frac{1}{2}}\eta} \right), \quad \xi \left( \omega_{\xi, u^* B^{\frac{1}{2}}\eta} \right) = \lambda^{\frac{1}{4}} J u^* J \xi \left( \omega_{\xi, A^{-\frac{1}{2}}\eta} \right).$$

*The following set is a  $\sigma$ -weak-weak core for  $\Lambda_2$ :*

$$\mathcal{D} = \left\{ (x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega) \mid x \in C_1^0, \omega_{\xi, \eta} \in C_2 \right\}.$$

*Moreover, if  $x \in C_1$  and  $\omega_{\xi, \eta} \in C_2$ , then*

$$\Lambda_2((x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega)) = \Lambda_P(x) \otimes \xi(\omega_{\xi, A^{-\frac{1}{2}}\eta}).$$

**Proof.** Let  $\omega_{\xi,\eta} \in \mathcal{I}_\Omega$  and  $\eta \in \mathcal{D}(A^{-\frac{1}{2}})$ . Let  $e_n$  be self-adjoint elements, like in Lemma 2, for the operator  $A$ . When  $x \in \mathcal{N}_\varphi$ , we have

$$\begin{aligned} |\omega_{\xi, A^{-\frac{1}{2}}\eta}(e_n x^*)| &= |\langle e_n x^* \xi, A^{-\frac{1}{2}}\eta \rangle| = |\langle (A^{-\frac{1}{2}}e_n)x^* \xi, \eta \rangle| \\ &= |\langle (xA^{-\frac{1}{2}}e_n)^* \xi, \eta \rangle| \leq C \|\Lambda_\Omega(xA^{-\frac{1}{2}}e_n)\|, \end{aligned}$$

because  $xA^{-\frac{1}{2}}e_nA^{\frac{1}{2}}$  is bounded and its closure, which equals to  $xe_n$ , belongs to  $\mathcal{N}_\varphi$ . Thus, we obtain

$$|\omega_{\xi, A^{-\frac{1}{2}}\eta}(e_n x^*)| \leq C \|\Lambda(xe_n)\| = C \|J\sigma_{-\frac{i}{2}}(e_n)J\Lambda(x)\| \rightarrow C \|\Lambda(x)\|.$$

Since  $|\omega_{\xi, A^{-\frac{1}{2}}\eta}(e_n x^*)| \rightarrow |\omega_{\xi, A^{-\frac{1}{2}}\eta}(x^*)|$ , we conclude that  $\omega_{\xi, A^{-\frac{1}{2}}\eta}$  is in  $\mathcal{I}$ . Moreover, for all  $x \in \mathcal{N}_\varphi$ , we have

$$\begin{aligned} \langle \xi_\Omega(\omega_{\xi,\eta}), J\sigma_{-\frac{i}{2}}(e_n)J\Lambda(x) \rangle &= \langle \xi_\Omega(\omega_{\xi,\eta}), \Lambda(xe_n) \rangle = \langle \xi_\Omega(\omega_{\xi,\eta}), \Lambda_\Omega(xA^{-\frac{1}{2}}e_n) \rangle \\ &= \omega_{\xi,\eta}(A^{-\frac{1}{2}}e_n x^*) = \langle e_n x^* \xi, A^{-\frac{1}{2}}\eta \rangle \\ &= \omega_{\xi, A^{-\frac{1}{2}}\eta}(e_n x^*) = \langle \xi(\omega_{\xi, A^{-\frac{1}{2}}\eta}), \Lambda(xe_n) \rangle \\ &= \langle \xi(\omega_{\xi, A^{-\frac{1}{2}}\eta}), J\sigma_{-\frac{i}{2}}(e_n)J\Lambda(x) \rangle. \end{aligned}$$

Taking the limit when  $n \rightarrow \infty$ , we conclude that  $\xi_\Omega(\omega_{\xi,\eta}) = \xi(\omega_{\xi, A^{-\frac{1}{2}}\eta})$ .

Suppose that  $\eta \in \mathcal{D}(B^{\frac{1}{2}})$ . Let  $f_m$  be self-adjoint elements, like in Lemma 2, for the operator  $B$ . Note that  $f_m$  commute with  $e_n$  and  $u$ , also  $e_n$  commute with  $u$ . Let us show that  $uB^{\frac{1}{2}}f_mA^{\frac{1}{2}}e_n$  is analytic w.r.t.  $\sigma$ . We have

$$\Psi(-(g - \gamma_t), g - \gamma_t) = \lambda^{-it^2} \Psi(-g, g) \Psi(g, \gamma_t) \Psi(\gamma_t, g),$$

so  $\sigma_t(u) = \lambda^{-it^2} uA^{-it}B^{-it}$  and, using Lemma 2, we obtain

$$\begin{aligned} \sigma_t(uB^{\frac{1}{2}}f_mA^{\frac{1}{2}}e_n) &= \lambda^{-it^2} uA^{-it}B^{-it}B^{\frac{1}{2}}\sigma_t(f_m)A^{\frac{1}{2}}\sigma_t(e_n) \\ &= \lambda^{-it^2} uB^{\frac{1}{2}-it}\sigma_t(f_m)A^{\frac{1}{2}-it}\sigma_t(e_n). \end{aligned}$$

Define the following function from  $\mathbb{C}$  to  $M$ :

$$f(z) = \lambda^{-iz^2} uB^{\frac{1}{2}-iz}\sigma_z(f_m)A^{\frac{1}{2}-iz}\sigma_z(e_n).$$

By Lemma 2,  $f$  is analytic, so  $uB^{\frac{1}{2}}f_mA^{\frac{1}{2}}e_n$  is analytic, and we have

$$\sigma_{-\frac{i}{2}}(uB^{\frac{1}{2}}f_mA^{\frac{1}{2}}e_n) = \lambda^{\frac{i}{4}} u\sigma_{-\frac{i}{2}}(f_m)\sigma_{-\frac{i}{2}}(e_n).$$

Thus, for  $x \in \mathcal{N}_\varphi$ ,  $xu^*B^{\frac{1}{2}}f_mA^{\frac{1}{2}}e_n$  is bounded and its closure, which is equal to  $xu^*B^{\frac{1}{2}}f_mA^{\frac{1}{2}}e_n$ , belongs to  $\mathcal{N}_\varphi$ . Moreover,

$$\begin{aligned} |\omega_{\xi, u^*B^{\frac{1}{2}}\eta}(e_n f_m x^*)| &= |\langle e_n f_m x^* \xi, u^*B^{\frac{1}{2}}\eta \rangle| = |\langle B^{\frac{1}{2}}f_m e_n u x^* \xi, \eta \rangle| \\ &= |\langle (xu^*B^{\frac{1}{2}}f_m e_n)^* \xi, \eta \rangle| \leq C \|\Lambda(xu^*B^{\frac{1}{2}}f_mA^{\frac{1}{2}}e_n)\| \\ &\leq C \|J\lambda^{\frac{i}{4}} u\sigma_{-\frac{i}{2}}(f_m)\sigma_{-\frac{i}{2}}(e_n)J\Lambda(x)\|. \end{aligned}$$

Taking the limit over  $m$  and  $n$ , we get

$$|\omega_{\xi, u^* B^{\frac{1}{2}} \eta}(x^*)| \leq C \|JuJ\Lambda(x)\| \leq C \|u\| \|\Lambda(x)\|.$$

Thus,  $\omega_{\xi, u^* B^{\frac{1}{2}} \eta} \in \mathcal{I}$ . Moreover, for all  $x \in \mathcal{N}_\varphi$ , one has

$$\begin{aligned} & \langle \xi(\omega_{\xi, u^* B^{\frac{1}{2}} \eta}), J\sigma_{-\frac{i}{2}}(e_n)\sigma_{-\frac{i}{2}}(f_m)J\Lambda(x) \rangle = \langle \xi(\omega_{\xi, u^* B^{\frac{1}{2}} \eta}), \Lambda(xe_n f_m) \rangle \\ & = \omega_{\xi, u^* B^{\frac{1}{2}} \eta}(e_n f_m x^*) = \langle e_n f_m x^* \xi, u^* B^{\frac{1}{2}} \eta \rangle = \langle x^* \xi, u^* B^{\frac{1}{2}} f_m A^{\frac{1}{2}} e_n A^{-\frac{1}{2}} \eta \rangle \\ & = \langle u B^{\frac{1}{2}} f_m A^{\frac{1}{2}} e_n x^* \xi, A^{-\frac{1}{2}} \eta \rangle = \omega_{\xi, A^{-\frac{1}{2}} \eta} \left( (x u^* B^{\frac{1}{2}} f_m A^{\frac{1}{2}} e_n)^* \right) \\ & = \langle \xi(\omega_{\xi, A^{-\frac{1}{2}} \eta}), \Lambda(x u^* B^{\frac{1}{2}} f_m A^{\frac{1}{2}} e_n) \rangle = \langle \xi(\omega_{\xi, A^{-\frac{1}{2}} \eta}), J\lambda^{\frac{i}{4}} u \sigma_{-\frac{i}{2}}(f_m) \sigma_{-\frac{i}{2}}(e_n) J\Lambda(x) \rangle \\ & = \langle \lambda^{\frac{i}{4}} Ju^* J\xi(\omega_{\xi, A^{-\frac{1}{2}} \eta}), J\sigma_{-\frac{i}{2}}(e_n)\sigma_{-\frac{i}{2}}(f_m)J\Lambda(x) \rangle. \end{aligned}$$

Taking the limit over  $m$  and  $n$ , we get  $\xi(\omega_{\xi, u^* B^{\frac{1}{2}} \eta}) = \lambda^{\frac{i}{4}} Ju^* J\xi(\omega_{\xi, A^{-\frac{1}{2}} \eta})$ . Now we want to prove that  $\mathcal{D}$  is a  $\sigma$ -weak-weak core for  $\Lambda_2$ . Because  $T = T_1 \otimes 1$ , we know that  $T^{\frac{1}{2}}(x \otimes 1)$  is bounded if and only if  $T_1^{\frac{1}{2}}x$  is bounded. Thus, by Proposition 18,  $C_1^0$  is a  $\sigma$ -strong\*-norm core for  $\Lambda_P$ , and, by Proposition 17, it suffices to show that the set  $\{(\omega \otimes \iota)(W_\Omega) \mid \omega \in C_2\}$  is a  $\sigma$ -strong\*-norm core for  $\hat{\Lambda}_\Omega$ . Let  $x = (\omega_{\xi, \eta} \otimes \iota)(W_\Omega)$  with  $\omega_{\xi, \eta} \in \mathcal{I}_\Omega$ . Let  $L = \mathbb{N} \times \mathbb{N}$  with the product order and consider the net  $x_{(n, m)} = (\omega_{\xi, e_n f_m \eta} \otimes \iota)(W_\Omega)$ . Because  $e_n f_m \eta \rightarrow \eta$ , we have  $x_{(n, m)} \rightarrow x$  in norm. Note that  $e_n f_m \eta \in \mathcal{D}(A^{-\frac{1}{2}}) \cap \mathcal{D}(B^{\frac{1}{2}})$ . Moreover, using the same techniques, one can show that  $\omega_{\xi, e_n f_m \eta} \in \mathcal{I}_\Omega$ . Thus,  $\overline{\omega_{\xi, e_n f_m \eta}} \in C_2$  and we have, for all  $x \in M$  such that  $x A^{\frac{1}{2}}$  is bounded and  $x A^{\frac{1}{2}} \in \mathcal{N}_\varphi$ ,

$$\begin{aligned} \langle \hat{\Lambda}_\Omega(x_{(n, m)}), \Lambda_\Omega(x) \rangle & = \langle \xi_\Omega(\omega_{\xi, e_n f_m \eta}), \Lambda_\Omega(x) \rangle = \langle x^* \xi, e_n f_m \eta \rangle \\ & = \langle (x e_n f_m)^* \xi, \eta \rangle = \langle \xi_\Omega(\omega_{\xi, \eta}), \Lambda_\Omega(x e_n f_m) \rangle, \end{aligned}$$

because  $x e_n f_m A^{\frac{1}{2}}$  is bounded and  $\overline{x e_n f_m A^{\frac{1}{2}}} = \overline{x A^{\frac{1}{2}} e_n f_m} \in \mathcal{N}_\varphi$ , so

$$\begin{aligned} \langle \hat{\Lambda}_\Omega(x_{(n, m)}), \Lambda_\Omega(x) \rangle & = \langle \xi_\Omega(\omega_{\xi, \eta}), J\sigma_{-\frac{i}{2}}(e_n)\sigma_{-\frac{i}{2}}(f_m)J\Lambda(\overline{x A^{\frac{1}{2}}}) \rangle \\ & = \langle J\sigma_{\frac{i}{2}}(e_n)\sigma_{\frac{i}{2}}(f_m)J\xi_\Omega(\omega_{\xi, \eta}), \Lambda_\Omega(x) \rangle \end{aligned}$$

Thus,  $\hat{\Lambda}_\Omega(x_{(n, m)}) = J\sigma_{\frac{i}{2}}(e_n)\sigma_{\frac{i}{2}}(f_m)J\hat{\Lambda}_\Omega(x) \rightarrow \hat{\Lambda}_\Omega(x)$ .  $\blacksquare$

Next proposition describes the image by  $\Lambda_1$  of typical elements from  $\Lambda_2$ . Let us define the unitaries

$$U = (\lambda_L^{\hat{G}^2} \otimes \alpha)(\Psi^\circ)^* \quad \text{and} \quad V = (\lambda_R^{\hat{G}^2} \otimes \alpha')(\sigma\Psi^*).$$

**Proposition 9** *Let  $x \in C_1^0$  and  $\omega \in M_*$  be such that  $\omega u \in \mathcal{I}$ , then  $\Lambda_P \otimes \xi(\omega u) \in \mathcal{D}(T^{-\frac{1}{2}})$ ,  $(x \otimes 1)(\omega \otimes \iota)(\tilde{W}_\Omega) \in \mathcal{N}_{\varphi_1}$  and*

$$\Lambda_1 \left( (x \otimes 1)(\omega \otimes \iota)(\tilde{W}_\Omega) \right) = UV T^{-\frac{1}{2}} \Lambda_P(x) \otimes \xi(\omega u).$$

First, we need some preliminary results.

**Lemma 10** *Let  $J_1$  be the modular conjugation associated with  $\varphi_1$ . Then, for all  $F \in L^\infty(G)$ ,*

$$(\lambda_L^{\hat{G}^2} \otimes \alpha)(\Delta_G(F)) = J_1 \lambda_L(F)^* J_1.$$

**Proof.** Using Lemma 8 (3), we see that  $((\gamma_1, \gamma_2) \mapsto L_{\gamma_1} R_{\gamma_2})$  is the standard implementation of the action  $\alpha$  on  $H = H_{\hat{\varphi}}$ , so the operator  $J_1$  is given by  $J_1 \xi(\gamma_1, \gamma_2) = L_{-\gamma_1} R_{-\gamma_2} \hat{J} \xi(-\gamma_1, -\gamma_2)$ , for  $\xi \in L^2(\hat{G}^2, H)$ . It is now easy to check the needed equality for  $F = u_\gamma$  with  $\gamma \in \hat{G}$ . Because  $(\lambda_L^{\hat{G}^2} \otimes \alpha) \circ \Delta_G$  and  $J_1 \lambda_L(\cdot)^* J_1$  are  $*$ -homomorphisms, this concludes the proof.  $\blacksquare$

Define one parameter groups of automorphisms of  $L^\infty(G) : \gamma_t(F)(x) = F(x - \gamma_t)$  and of  $M' : \sigma'_t(x) = J \sigma_t(JxJ) J$ . Note that  $\sigma'_t \circ \alpha' = \alpha' \circ \gamma_t$ . By analytic continuation,  $\alpha'(F) \in \mathcal{D}(\sigma'_z)$  and  $\sigma'_z(\alpha'(F)) = \alpha'(\gamma_z(F)) \forall z \in \mathbb{C}, F \in \mathcal{D}(\gamma_z)$ .

**Lemma 11** *Let  $F \in L^\infty(G^2)$ ,  $x \in \mathcal{N}_{\varphi_P}$ , and  $\omega \in \mathcal{I}$ . If  $F \in \mathcal{D}(\gamma_{-\frac{i}{2}} \otimes \iota)$ , then  $(\lambda_R^{\hat{G}^2} \otimes \alpha')(\sigma F) \in \mathcal{D}(\iota \otimes \sigma'_{-\frac{i}{2}})$ ,  $(x \otimes 1)(\omega \otimes \iota) \left( (\alpha \otimes \lambda_R)(F) \tilde{W}(\alpha \otimes \lambda_L)(F) \right) \in \mathcal{N}_{\varphi_1}$ , and*

$$\begin{aligned} & \Lambda_1 \left( (x \otimes 1)(\omega \otimes \iota) \left( (\alpha \otimes \lambda_R)(F) \tilde{W}(\alpha \otimes \lambda_L)(F) \right) \right) \\ &= (\lambda_L^{\hat{G}^2} \otimes \alpha)(F^\circ)(\iota \otimes \sigma'_{-\frac{i}{2}}) \left( (\lambda_R^{\hat{G}^2} \otimes \alpha')(\sigma F) \right) \Lambda_P(x) \otimes \xi(\omega). \end{aligned}$$

**Proof.** Because  $\mathcal{D}(\gamma_{-\frac{i}{2}}) \odot L^\infty(G)$  is a  $\sigma$ -strong\* core for  $\gamma_{-\frac{i}{2}} \otimes \iota$  and  $\Lambda_1$  is  $\sigma$ -weak-weak closed, we can take  $F \in \mathcal{D}(\gamma_{-\frac{i}{2}}) \odot L^\infty(G)$ . By linearity, we can take  $F = F_1 \otimes F_2$  with  $F_1 \in \mathcal{D}(\gamma_{-\frac{i}{2}})$  and  $F_2 \in L^\infty(G)$ . If  $x \in \mathcal{N}_{\varphi_P}$  and  $\omega \in \mathcal{I}$ , then

$$\begin{aligned} & (x \otimes 1)(\omega \otimes \iota) \left( (\alpha \otimes \lambda_R)(F) \tilde{W}(\alpha \otimes \lambda_L)(F) \right) \\ &= \lambda_R(F_2)(x \otimes 1)(\alpha(F_1) \cdot \omega \cdot \alpha(F_1) \otimes \iota)(\tilde{W}) \lambda_L(F_2). \end{aligned}$$

Because  $F_1 \in \mathcal{D}(\gamma_{-\frac{i}{2}})$ , we have  $\alpha(F_1) \in \mathcal{D}(\sigma_{-\frac{i}{2}})$ . Lemma 3 and the definition of  $\Lambda_1$  imply  $(x \otimes 1)(\alpha(F_1) \cdot \omega \cdot \alpha(F_1) \otimes \iota)(\tilde{W}) \in \mathcal{N}_{\varphi_1}$  and

$$\begin{aligned} & \Lambda_1 \left( (x \otimes 1)(\alpha(F_1) \cdot \omega \cdot \alpha(F_1) \otimes \iota)(\tilde{W}) \right) \\ &= (1 \otimes \alpha(F_1))(1 \otimes J \sigma_{-\frac{i}{2}}(\alpha(F_1)^* J)(\Lambda_P(x) \otimes \xi(\omega))) \\ &= (1 \otimes \alpha(F_1))(1 \otimes \alpha'(\gamma_{-\frac{i}{2}}(F_1)))(\Lambda_P(x) \otimes \xi(\omega)). \end{aligned}$$

Moreover, (14) gives  $\lambda_L(F_2) \in N^{\varphi_1}$ , so

$$\begin{aligned} & \lambda_R(F_2)(x \otimes 1)(\alpha(F_1) \cdot \omega \cdot \alpha(F_1) \otimes \iota)(\tilde{W}) \lambda_L(F_2) \in \mathcal{N}_{\varphi_1} \quad \text{and,} \\ & \Lambda_1 \left( \lambda_R(F_2)(x \otimes 1)(\alpha(F_1) \cdot \omega \cdot \alpha(F_1) \otimes \iota)(\tilde{W}) \lambda_L(F_2) \right) \\ &= J_1 \lambda_L(F_2)^* J_1 \lambda_R(F_2)(1 \otimes \alpha(F_1))(1 \otimes \alpha'(\gamma_{-\frac{i}{2}}(F_1)))(\Lambda_P(x) \otimes \xi(\omega)) \\ &= J_1 \lambda_L(F_2)^* J_1 (1 \otimes \alpha(F_1)) \left( (\lambda_R^{\hat{G}^2}(F_2) \otimes 1)(1 \otimes \alpha'(\gamma_{-\frac{i}{2}}(F_1))) \right) (\Lambda_P(x) \otimes \xi(\omega)) \\ & \quad (\text{because } \lambda_R(F_2) = \lambda_R^{\hat{G}^2}(F_2) \otimes 1 \text{ commute with } 1 \otimes \alpha(F_1)) \\ &= (\lambda_L^{\hat{G}^2} \otimes \alpha)(\Delta_G(F_2) 1 \otimes F_1)(\lambda_R^{\hat{G}^2} \otimes \alpha')((F_2 \otimes 1)(1 \otimes \gamma_{-\frac{i}{2}}(F_1)))(\Lambda_P(x) \otimes \xi(\omega)), \end{aligned}$$

where we used Lemma 10 in the last equality. Note that

$$(\Delta_G(F_2)1 \otimes F_1)(g, h) = F_2(g + h)F_1(h) = F(h, g + h) = F^\circ(g, h),$$

and because

$$\begin{aligned} (\lambda_R^{\hat{G}^2} \otimes \alpha')((F_2 \otimes 1)(1 \otimes \gamma_{-\frac{i}{2}}(F_1))) &= (\lambda_R^{\hat{G}^2} \otimes \alpha')((\iota \otimes \gamma_{-\frac{i}{2}})(\sigma F)) \\ &= (\iota \otimes \sigma'_{-\frac{i}{2}})((\lambda_R^{\hat{G}^2} \otimes \alpha')(\sigma F)), \end{aligned}$$

we conclude the proof.  $\blacksquare$

**Lemma 12** *The operator  $(\iota \otimes \sigma'_{-\frac{i}{2}})(V)$  is normal, affiliated with  $\mathcal{L}(\hat{G}^2) \otimes M'$ , and its polar decomposition is  $(\iota \otimes \sigma'_{-\frac{i}{2}})(V) = V(T_1^{-\frac{1}{2}} \otimes 1) = VT^{-\frac{1}{2}}$ .*

**Proof.** We have  $(\iota \otimes \gamma_t)(\sigma\Psi^*)(g, h) = \Psi^*(h, g)\Psi^*(-\gamma_t, g)$ , so

$$(\iota \otimes \sigma'_t)(V) = (\lambda_R^{\hat{G}^2} \otimes \alpha')((\iota \otimes \gamma_t)(\sigma\Psi^*)) = V(T_1^{-it} \otimes 1).$$

We conclude the proof by applying Proposition 1.  $\blacksquare$

*Proof of Proposition 9.* Let  $x \in \mathcal{C}_1^0$  and  $\omega \in M_*$  such that  $\omega \cdot u \in \mathcal{I}$ . By Lemma 12,  $\Lambda_P(x) \otimes \xi(\omega \cdot u) \in \mathcal{D}((\iota \otimes \sigma'_{-\frac{i}{2}})(V))$  and

$$(\iota \otimes \sigma'_{-\frac{i}{2}})(V)\Lambda_P(x) \otimes \xi(\omega \cdot u) = VT^{-\frac{1}{2}}\Lambda_P(x) \otimes \xi(\omega \cdot u).$$

By Lemma 1,  $V(n) \rightarrow V$   $\sigma$ -strongly\* and

$$(\iota \otimes \sigma'_{-\frac{i}{2}})(V(n))\Lambda_P(x) \otimes \xi(\omega \cdot u) \rightarrow VT^{-\frac{1}{2}}\Lambda_P(x) \otimes \xi(\omega \cdot u),$$

where

$$V(n) = \sqrt{\frac{n}{\pi}} \int e^{-nt^2} (\iota \otimes \sigma'_t)(V) dt = (\lambda_R^{\hat{G}^2} \otimes \alpha')(\sigma\Psi^*(n)),$$

with  $\Psi^*(n) = \sqrt{\frac{n}{\pi}} \int e^{-nt^2} (\gamma_t \otimes \iota)(\Psi^*) dt$ . So  $\Psi^*(n)$  is analytic w.r.t.  $(t \mapsto \gamma_t \otimes \iota)$  and  $\Psi^*(n) \rightarrow \Psi^*$   $\sigma$ -strongly\*. Now we can apply Lemma 11 to  $\Psi^*(n)$  and  $\omega \cdot u : (x \otimes 1)(\omega \cdot u \otimes \iota) \left( (\alpha \otimes \lambda_R)(\Psi^*(n)) \tilde{W}(\alpha \otimes \lambda_L)(\Psi^*(n)) \right) \in \mathcal{N}_{\varphi_1}$  and

$$\begin{aligned} \Lambda_1 \left( (x \otimes 1)(\omega \cdot u \otimes \iota) \left( (\alpha \otimes \lambda_R)(\Psi^*(n)) \tilde{W}(\alpha \otimes \lambda_L)(\Psi^*(n)) \right) \right) \\ = (\lambda_L^{\hat{G}^2} \otimes \alpha)(\Psi^*(n)^\circ) (\iota \otimes \sigma'_{-\frac{i}{2}})(V(n))\Lambda_P(x) \otimes \xi(\omega \cdot u). \end{aligned}$$

Note that

$(\alpha \otimes \lambda_R)(\Psi^*(n)) \tilde{W}(\alpha \otimes \lambda_L)(\Psi^*(n)) \rightarrow (\alpha \otimes \lambda_R)(\Psi^*) \tilde{W}(\alpha \otimes \lambda_L)(\Psi^*)$   $\sigma$ -weakly, so,  
 $(x \otimes 1)(\omega \cdot u \otimes \iota) \left( (\alpha \otimes \lambda_R)(\Psi^*(n)) \tilde{W}(\alpha \otimes \lambda_L)(\Psi^*(n)) \right) \rightarrow (x \otimes 1)(\omega \otimes \iota)(\tilde{W}_\Omega)$   $\sigma$ -weakly,  
and

$(\lambda_L^{\hat{G}^2} \otimes \alpha)(\Psi^*(n)^\circ) (\iota \otimes \sigma'_{-\frac{i}{2}})(V(n))\Lambda_P(x) \otimes \xi(\omega \cdot u) \rightarrow UV T^{-\frac{1}{2}} \Lambda_P(x) \otimes \xi(\omega \cdot u)$  weakly.

Because  $\Lambda_1$  is  $\sigma$ -weak-closed, this concludes the proof.

**Lemma 13** *Let  $\eta \in \mathcal{D}(B^{\frac{1}{2}})$ ,  $\xi \in H$  and  $x \in \mathcal{C}_1$ . Then*

*$(x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega)T^{\frac{1}{2}}$  is bounded and its closure is  $\overline{T^{\frac{1}{2}}(x \otimes 1)(\omega_{\xi, B^{\frac{1}{2}}\eta} \otimes \iota)(\tilde{W}_\Omega)}$ .*

**Proof.** Using (15), for all  $t \in \mathbb{R}$ , we have  $\tilde{W}_\Omega(1 \otimes T^{it})\tilde{W}_\Omega^* = B^{it} \otimes T^{it}$ , so  $\tilde{W}_\Omega(1 \otimes T^{\frac{1}{2}})\tilde{W}_\Omega^* = B^{\frac{1}{2}} \otimes T^{\frac{1}{2}}$ . Let  $\eta \in \mathcal{D}(B^{\frac{1}{2}})$ ,  $\xi \in H$ ,  $x \in \mathcal{C}_1$ ,  $f \in \mathcal{D}(T^{\frac{1}{2}})$ , and  $l \in L^2(\hat{G}^2, H)$ , then

$$\begin{aligned} \langle (x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega)T^{\frac{1}{2}}f, l \rangle &= \langle \tilde{W}_\Omega\xi \otimes T^{\frac{1}{2}}f, \eta \otimes (x \otimes 1)^*l \rangle \\ &= \langle (B^{\frac{1}{2}} \otimes T^{\frac{1}{2}})\tilde{W}_\Omega\xi \otimes f, \eta \otimes (x \otimes 1)^*l \rangle \\ &= \langle (1 \otimes (x \otimes 1)T^{\frac{1}{2}})\tilde{W}_\Omega\xi \otimes f, B^{\frac{1}{2}}\eta \otimes l \rangle \\ &= \langle \overline{T^{\frac{1}{2}}(x \otimes 1)(\omega_{\xi, B^{\frac{1}{2}}\eta} \otimes \iota)(\tilde{W}_\Omega)}f, l \rangle. \end{aligned}$$

Thus, we have  $(x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega)T^{\frac{1}{2}} \subset \overline{T^{\frac{1}{2}}(x \otimes 1)(\omega_{\xi, B^{\frac{1}{2}}\eta} \otimes \iota)(\tilde{W}_\Omega)}$ . Because  $\mathcal{D}(T^{\frac{1}{2}})$  is dense, this concludes the proof.  $\blacksquare$

**Proposition 10** *Let  $x \in \mathcal{C}_1^0$  and  $\omega_{\xi, \eta} \in C_2$ . Then*

$$(x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega) \in \mathcal{N}_\mu \cap \mathcal{N}_{\varphi_2} \quad \text{and}$$

$$\Lambda_\mu \left( (x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega) \right) = \lambda^{\frac{1}{4}}UV(1 \otimes Ju^*J)\Lambda_2 \left( (x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega) \right).$$

**Proof.** Let  $x \in \mathcal{C}_1^0$  and  $\omega_{\xi, \eta} \in C_2$ . By Lemma 13,  $(x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega)T^{\frac{1}{2}}$  is bounded and its closure is  $\overline{T^{\frac{1}{2}}(x \otimes 1)(\omega_{\xi, B^{\frac{1}{2}}\eta} \otimes \iota)(\tilde{W}_\Omega)}$ . Moreover, by Lemma 9,  $\omega_{\xi, B^{\frac{1}{2}}\eta} \cdot u = \omega_{\xi, u^*B^{\frac{1}{2}}\eta} \in \mathcal{I}$ , so we can apply Proposition 9, and we find that  $(x \otimes 1)(\omega_{\xi, B^{\frac{1}{2}}\eta} \otimes \iota)(\tilde{W}_\Omega) \in \mathcal{N}_{\varphi_1}$  and

$$\Lambda_1 \left( (x \otimes 1)(\omega_{\xi, B^{\frac{1}{2}}\eta} \otimes \iota)(\tilde{W}_\Omega) \right) = UV T^{-\frac{1}{2}} \Lambda_P(x) \otimes \xi(\omega_{\xi, u^*B^{\frac{1}{2}}\eta}).$$

Finally, using Proposition 18, and because  $T^{\frac{1}{2}}$  commutes with  $UV$ , we find that  $\overline{T^{\frac{1}{2}}(x \otimes 1)(\omega_{\xi, B^{\frac{1}{2}}\eta} \otimes \iota)(\tilde{W}_\Omega)} \in \mathcal{N}_{\varphi_1}$  and

$$\Lambda_1 \left( \overline{T^{\frac{1}{2}}(x \otimes 1)(\omega_{\xi, B^{\frac{1}{2}}\eta} \otimes \iota)(\tilde{W}_\Omega)} \right) = UV \Lambda_P(x) \otimes \xi(\omega_{\xi, u^*B^{\frac{1}{2}}\eta}).$$

By Lemma 9,  $\xi(\omega_{\xi, u^*B^{\frac{1}{2}}\eta}) = \lambda^{\frac{1}{4}}Ju^*J\xi_\Omega(\omega_{\xi, \eta})$ , so

$$\begin{aligned} \Lambda_1 \left( \overline{T^{\frac{1}{2}}(x \otimes 1)(\omega_{\xi, B^{\frac{1}{2}}\eta} \otimes \iota)(\tilde{W}_\Omega)} \right) &= \lambda^{\frac{1}{4}}UV(1 \otimes Ju^*J)\Lambda_P(x) \otimes \xi_\Omega(\omega_{\xi, \eta}) \\ &= \lambda^{\frac{1}{4}}UV(1 \otimes Ju^*J)\Lambda_2 \left( (x \otimes 1)(\omega_{\xi, \eta} \otimes \iota)(\tilde{W}_\Omega) \right). \end{aligned}$$

$\blacksquare$  *Proof of Theorem 6.* Let  $\mathcal{D}$  be the  $\sigma$ -weak-weak core for  $\Lambda_2$  introduced before Lemma 9. By Proposition 10,  $\mathcal{D} \subset \mathcal{N}_\mu \cap \mathcal{N}_{\varphi_2}$  and there is a unitary  $Z$  such that  $\Lambda_2(x) = Z\Lambda_\mu(x)$ , for all  $x \in \mathcal{D}$ . By Proposition 19,  $\varphi_2 = \tilde{\mu}_\Omega$ , so  $\hat{\varphi}_\Omega = \mu_\Omega$ .

## 5 Examples

### 5.1 Twisting of the $az + b$ group

Our aim is to prove Theorem 3. According to Section 2.7, if  $H$  is a closed abelian subgroup of a l.c. group  $G$ , then  $H < (\mathcal{L}(G), \hat{\Delta}_G)$  is an abelian stable co-subgroup. The morphism  $\alpha : L^\infty(\hat{H}) \rightarrow \mathcal{L}(G)$  is given by  $\alpha(u_h) = \lambda_G(h)$ , and the morphism  $(t \mapsto \gamma_t) : \mathbb{R} \rightarrow \hat{H}$  by  $\langle \gamma_t, h \rangle = \delta_G^{-it}(h)$ . Let  $G = \mathbb{C}^* \ltimes \mathbb{C}$  and  $K \subset G$  be the subgroup  $K = \{(z, 0), z \in \mathbb{C}^*\}$ . The modular function of  $G$  is  $\delta_G(z, w) = |z|^{-1}$ , for all  $z \in \mathbb{C}^*$ ,  $w \in \mathbb{C}$ , and  $\langle \gamma_t, z \rangle = |z|^{it}$ , for all  $z \in \mathbb{C}^*$ ,  $t \in \mathbb{R}$ . Let us identify  $\widehat{\mathbb{C}^*}$  with  $\mathbb{Z} \times \mathbb{R}_+^*$ :

$$\mathbb{Z} \times \mathbb{R}_+^* \rightarrow \widehat{\mathbb{C}^*}, \quad (n, \rho) \mapsto \gamma_{n, \rho} = (re^{i\theta} \mapsto e^{i \ln r \ln \rho} e^{in\theta}).$$

Then  $\gamma_t = (0, e^t) \in \mathbb{Z} \times \mathbb{R}_+^*$ . For any  $x \in \mathbb{R}$ , there is a bicharacter on  $\mathbb{Z} \times \mathbb{R}_+^*$  :  $\Psi_x((n, \rho), (k, r)) = e^{ix(k \ln \rho - n \ln r)}$ . Let  $(M_x, \Delta_x)$  be the l.c. quantum group obtained by twisting. Then  $\Psi_x((n, \rho), \gamma_t^{-1}) = e^{ixtn} = u_{e^{ixt}}((n, \rho))$ , and we get the operator  $A_x$  deforming the Plancherel weight  $\varphi$ :

$$A_x^{it} = \alpha(u_{e^{2ixt}}) = \lambda_{(e^{2ix}, 0)}^G.$$

Since  $\Psi_x(\gamma_t, \gamma_s) = 1$ , for all  $s, t \in \mathbb{R}$ , the twisted left-invariant weight  $\varphi_x$  satisfies  $[D\varphi_x : D\varphi]_t = A_x^{it} = \lambda_{(e^{itx}, 0)}^G$ . The modular element of the twisted quantum group is

$$\delta_x^{it} = \alpha(\Psi_x(\cdot, \gamma_t)\Psi_x(-\gamma_t, \cdot)) = \lambda_{(e^{-2itx}, 0)}^G,$$

so  $\delta_x$  is not affiliated with the center of  $\mathcal{L}(G)$ , and the twisted quantum group is not a Kac algebra. Let us look if  $(M_x, \Delta_x)$  is isomorphic for different values of  $x$ . Since  $\Psi_x$  is antisymmetric,  $\Psi_{-x} = \Psi_x^*$ , and  $\Delta$  is cocommutative, we have  $\Delta_{-x} = \sigma\Delta_x$ . Thus,  $(M_{-x}, \Delta_{-x}) \simeq (M_x, \Delta_x)^{\text{op}}$ . Moreover, using the Fourier transformation in the first variable, one has immediately  $\text{Sp}(\delta_x) = q_x^{\mathbb{Z}} \cup \{0\}$ , where  $q_x = e^{-2x}$ . Thus, if  $x \neq y$ ,  $x > 0, y > 0$ , one has  $q_x^{\mathbb{Z}} \neq q_y^{\mathbb{Z}}$  and, consequently,  $(M_x, \Delta_x)$  and  $(M_y, \Delta_y)$  are not isomorphic.

In order to finish the proof of Theorem 3, we must compute the dual l.c. quantum group. The action of  $K^2$  on  $L^\infty(G)$  can be lifted to its Lie algebra  $\mathbb{C}^2$  which does not change the result of deformation (see [6]) but simplifies calculations. The group  $\mathbb{C}$  is self-dual with the duality  $(z_1, z_2) \mapsto \exp(i\text{Im}(z_1 z_2))$ . Let  $x \in \mathbb{R}$ . The lifted bicharacter on  $\mathbb{C}$  is  $\Psi_x(z_1, z_2) = \exp(ix\text{Im}(z_1 \bar{z}_2))$ . The action  $\rho$  of  $\mathbb{C}^2$  on  $L^\infty(G)$  is

$$\rho_{z_1, z_2}(f)(w_1, w_2) = f(e^{z_2 - z_1} w_1, e^{-z_1} w_2). \quad (16)$$

Let  $N = \mathbb{C}^2 \ltimes L^\infty(G)$  and  $\theta$  be the dual action of  $\mathbb{C}^2$  on  $N$ . One has, for all  $z, w \in \mathbb{C}$ ,  $\Psi_x(w, z) = u_{x\bar{z}}(w)$ . So, the twisted dual action is

$$\theta_{z_1, z_2}^{\Psi_x} = \lambda_{-x\bar{z}_1, x\bar{z}_2} \theta_{z_1, z_2}(\cdot) \lambda_{-x\bar{z}_1, x\bar{z}_2}^*. \quad (17)$$

Let  $\widehat{M_x}$  be the fixed point algebra. We will construct two operators affiliated with  $M_x$  which generate  $\widehat{M_x}$ . Let  $a$  and  $b$  be the coordinate functions on  $G$ , and

$\alpha = \pi(a)$ ,  $\beta = \pi(b)$ . Then  $\alpha$  and  $\beta$  are normal operators affiliated with  $N$ , and (16) gives

$$\lambda_{z_1, z_2} \alpha \lambda_{z_1, z_2}^* = e^{z_2 - z_1} \alpha, \quad \lambda_{z_1, z_2} \beta \lambda_{z_1, z_2}^* = e^{-z_1} \beta. \quad (18)$$

Now, using (17) and (18), we find

$$\theta_{z_1, z_2}^{\Psi_x}(\alpha) = e^{x(\bar{z}_1 + \bar{z}_2)} \alpha, \quad \theta_{z_1, z_2}^{\Psi_x}(\beta) = e^{x\bar{z}_1} \beta. \quad (19)$$

Let  $T_l$  and  $T_r$  be the infinitesimal generators of the left and right translations, so  $T_l$  and  $T_r$  are affiliated with  $N$  and  $\lambda_{z_1, z_2} = \exp(i\text{Im}(z_1 T_l)) \exp(i\text{Im}(z_2 T_r))$ . Then  $\lambda(f) = f(T_l, T_r)$ , for all  $f \in L^\infty(\mathbb{C}^2)$ .

**Lemma 14** *Let  $L = e^{xT_l^*}$  and  $R = e^{xT_r^*}$ , then*

- $(\beta, L)$  is a  $e^x$ -commuting pair.
- $(\beta, R)$  is a 1-commuting pair.
- $(\alpha, R)$  is a  $e^{-x}$ -commuting pair.
- $(\alpha, L)$  is a  $e^x$ -commuting pair.

**Proof.** Note that  $\text{Ph}(L) = e^{-ix\text{Im}T_l} = \lambda_{-x, 0}$  and  $|L|^{is} = e^{isx\text{Re}T_l} = \lambda_{isx, 0}$ , so (18) gives  $|L|^{is}\beta|L|^{-is} = e^{-isx}\beta$  and  $\text{Ph}(L)\beta\text{Ph}(L)^* = e^x\beta$  which means that  $(\beta, L)$  is a  $e^x$ -commuting pair. The proof of the other assertions is similar. ■

Define  $U = \lambda(\Psi_x)$  and  $\hat{\alpha} = U^*\alpha U$ ,  $\hat{\nu} = \text{Ph}(L)\text{Ph}(\beta)$  and  $\hat{B} = |L||\beta|$ . Then  $\hat{\alpha}$  is normal,  $\hat{B}$  is positive self adjoint, both affiliated with  $N$ , and  $\hat{\nu} \in N$  is unitary.

**Proposition 11**  *$\hat{\alpha}$  and  $\hat{B}$  are affiliated with  $\widehat{M}_x$  and  $\hat{\nu} \in \widehat{M}_x$ . Moreover,*

$$\left\{ f(\hat{\alpha})g(\hat{B})h(\hat{\nu}), f \in L^\infty(\mathbb{C}), g \in L^\infty(\mathbb{R}_+^*), h \in L^\infty(\mathbb{S}^1) \right\}'' = \widehat{M}_x.$$

**Proof.** We have

$$\begin{aligned} \theta_{z_1, z_2}^{\Psi_x}(U) &= \lambda(\Psi_x(\cdot - z_1, \cdot - z_2)) \\ &= U e^{ix\text{Im}(-\bar{z}_2 T_l)} e^{ix\text{Im}(\bar{z}_1 T_r)} \Psi_x(z_1, z_2) \\ &= U \lambda_{-x\bar{z}_2, x\bar{z}_1} \Psi_x(z_1, z_2). \end{aligned}$$

This implies, using (19) and (18):

$$\theta_{z_1, z_2}^{\Psi_x}(\hat{\alpha}) = e^{x(\bar{z}_1 + \bar{z}_2)} U^* \lambda_{x\bar{z}_2, -x\bar{z}_1} \alpha \lambda_{x\bar{z}_2, -x\bar{z}_1}^* U = \hat{\alpha}.$$

Also,

$$\theta_{z_1, z_2}^{\Psi_x}(\hat{B}) = e^{x\text{Re}(T_l - \bar{z}_1)} e^{x\text{Re}(\bar{z}_1)} |\beta| = \hat{B}$$

and

$$\theta_{z_1, z_2}^{\Psi_x}(\hat{\nu}) = e^{ix\text{Im}(T_l^* - \bar{z}_1)} e^{ix\text{Im}(\bar{z}_1)} \text{Ph}(\beta) = \hat{\nu}.$$

Thus,  $\hat{\alpha}$  and  $\hat{B}$  are affiliated with  $\widehat{M}_x$  and  $\hat{v} \in \widehat{M}_x$ . Let

$$\mathcal{W} = \left\{ z f(\hat{\alpha}) g(\hat{B}) h(\hat{v}) y, f \in L^\infty(\mathbb{C}), g \in L^\infty(\mathbb{R}_+^*), h \in L^\infty(\mathbb{S}^1), z, y \in \lambda(L^\infty(\mathbb{C}^2)) \right\}''.$$

By Lemma 15, it suffices to show that  $\mathcal{W} = N$ . Note that

$$\left\{ z f(\hat{\alpha}), f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' = \left\{ z U^* f(\alpha) U, f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}''.$$

Substituting  $z \mapsto zU$ , we get

$$\left\{ z f(\hat{\alpha}), f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' = \left\{ z f(\alpha) U, f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}''.$$

Observe that

$$\left\{ z f(\alpha) z, f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' = \left\{ z f(\alpha), f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' ,$$

so

$$\left\{ z f(\hat{\alpha}), f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' = \left\{ f(\alpha) z U, f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}''.$$

Substituting  $z \mapsto zU^*$ , we get

$$\left\{ z f(\hat{\alpha}), f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' = \left\{ f(\alpha) z, f \in L^\infty(\mathbb{C}), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' ,$$

so

$$\mathcal{W} = \left\{ f(\alpha) z g(\hat{B}) h(\hat{v}) y, f \in L^\infty(\mathbb{C}), g \in L^\infty(\mathbb{R}_+^*), h \in L^\infty(\mathbb{S}^1), z, y \in \lambda(L^\infty(\mathbb{C}^2)) \right\}''.$$

Note that

$$\begin{aligned} \left\{ z g(\hat{B}), g \in L^\infty(\mathbb{R}_+^*), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' &= \left\{ z \hat{B}^{is}, s \in \mathbb{R}, z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' \\ &= \left\{ z e^{ist \operatorname{Re} T_i} |\beta|^{is}, s \in \mathbb{R}, z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' . \end{aligned}$$

Substitution  $z \mapsto z e^{-ist \operatorname{Re} T_i}$  gives

$$\begin{aligned} \left\{ z g(\hat{B}), g \in L^\infty(\mathbb{R}_+^*), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' &= \left\{ z |\beta|^{is}, s \in \mathbb{R}, z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' \\ &= \left\{ z g(|\beta|), g \in L^\infty(\mathbb{R}_+^*), z \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' . \end{aligned}$$

Also, one can prove that

$$\left\{ h(\hat{v}) y, h \in L^\infty(\mathbb{S}^1), y \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' = \left\{ h(\operatorname{Ph} \beta) y, h \in L^\infty(\mathbb{S}^1), y \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' .$$

Thus,

$$\begin{aligned} \mathcal{W} &= \left\{ f(\alpha) z g(|\beta|) h(\operatorname{Ph} \beta) y, f \in L^\infty(\mathbb{C}), g \in L^\infty(\mathbb{R}_+^*), h \in L^\infty(\mathbb{S}^1), z, y \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' \\ &= \left\{ f(\alpha) z g(\beta) y, f, g \in L^\infty(\mathbb{C}), z, y \in \lambda(L^\infty(\mathbb{C}^2)) \right\}'' . \end{aligned}$$

Commuting back  $f(\alpha)$  and  $z$ , we have the result.  $\blacksquare$

Let  $\hat{\beta} = \hat{v} \hat{B}$ . Then  $\hat{\beta}$  is a closed (non normal) operator affiliated with  $\widehat{M}_x$ . Let us give now the commutation relations between  $\hat{\alpha}$ ,  $\hat{\beta}$ .

**Proposition 12**  $\alpha$  and  $T_l^* + T_r^*$  strongly commute, and  $\hat{\alpha} = e^{x(T_l^* + T_r^*)}$ , so the polar decomposition of  $\hat{\alpha}$  is

$$Ph(\hat{\alpha}) = e^{-ix\text{Im}(T_l + T_r)} Ph(\alpha) = Ph(L)Ph(R)Ph(\alpha), \quad |\hat{\alpha}| = e^{x\text{Re}(T_l + T_r)} |\alpha| = |L||R||\alpha|.$$

Moreover, the following relations hold with  $q = e^{2x}$ :

- $\hat{\beta}\hat{\beta}^* = q\hat{\beta}^*\hat{\beta}$ ,
- $(\hat{\alpha}, \hat{\beta})$  is a  $\sqrt{q}$ -commuting pair.

**Proof.** Since

$$e^{i\text{Im}(z(T_l^* + T_r^*))} \alpha e^{-i\text{Im}(z(T_l^* + T_r^*))} = \lambda_{-\bar{z}, -\bar{z}} \alpha \lambda_{-\bar{z}, -\bar{z}}^* = e^{-\bar{z} + \bar{z}} \alpha = \alpha,$$

$T_l^* + T_r^*$  and  $\alpha$  strongly commute. Moreover, since  $e^{ix\text{Im}T_l T_l^*} = 1$ ,

$$\hat{\alpha} = e^{-ix\text{Im}T_l T_r^*} \alpha e^{ix\text{Im}T_l T_r^*} = e^{-ix\text{Im}T_l(T_l + T_r)^*} \alpha e^{ix\text{Im}T_l(T_l + T_r)^*}.$$

This equality, the strong commutativity of  $T_l^* + T_r^*$  with  $\alpha$ , and the equality  $e^{-ix\text{Im}T_l \omega} \alpha e^{ix\text{Im}T_l \omega} = e^{x\omega} \alpha$  imply  $\hat{\alpha} = e^{x(T_l^* + T_r^*)}$ . The polar decomposition of  $\hat{\alpha}$  follows. All the relations can be checked using Lemma 14.  $\blacksquare$

We shall give now a nice formula for  $\hat{\Delta}_x$ . Let us define the following (closed non-normal) operator affiliated with  $\widehat{M}_x \otimes \widehat{M}_x$ :  $\hat{\Delta}_x(\hat{\beta}) = \hat{\Delta}_x(\hat{v})\hat{\Delta}_x(\hat{B})$ .

**Proposition 13**

$$\hat{\Delta}_x(\hat{\alpha}) = \hat{\alpha} \otimes \hat{\alpha} \quad \text{and} \quad \hat{\Delta}_x(\hat{\beta}) = \hat{\alpha} \otimes \hat{\beta} + \hat{\beta} \otimes 1.$$

**Proof.** Proposition 7 gives  $\hat{\Delta}_x = \Upsilon\Gamma(\cdot)\Upsilon^*$ , where  $\Upsilon = e^{ix\text{Im}T_r \otimes T_l^*}$ , and  $\Gamma$  is uniquely characterized by two properties:

- $\Gamma(T_l) = T_l \otimes 1$ ,  $\Gamma(T_r) = 1 \otimes T_r$ ;
- $\Gamma$  restricted to  $L^\infty(G)$  coincides with the comultiplication  $\Delta_G$ .

With  $V = \Upsilon\Gamma(U^*)$ , we have  $\hat{\Delta}_x(\hat{\alpha}) = V(\alpha \otimes \alpha)V^*$ , so it suffices to show that  $(U \otimes U)V$  commutes with  $\alpha \otimes \alpha$ . Indeed in this case

$$\hat{\Delta}_x(\hat{\alpha}) = V(\alpha \otimes \alpha)V^* = (U^* \otimes U^*)(U \otimes U)V(\alpha \otimes \alpha)V^*(U^* \otimes U^*)(U \otimes U) = \hat{\alpha} \otimes \hat{\alpha}.$$

Let us show that  $(U \otimes U)V$  commutes with  $\alpha \otimes \alpha$ . From  $U = e^{ix\text{Im}T_l T_r^*}$  one has

$$\Gamma(U^*) = e^{-ix\text{Im}T_l \otimes T_r^*}, \quad U \otimes U = e^{ix\text{Im}(T_l T_r^* \otimes 1 + 1 \otimes T_l T_r^*)},$$

so  $V = e^{-ix\text{Im}(T_r^* \otimes T_l + T_l \otimes T_r^*)}$  and

$$(U \otimes U)V = e^{ix\text{Im}(T_l T_r^* \otimes 1 + 1 \otimes T_l T_r^* - T_r^* \otimes T_l - T_l \otimes T_r^*)}.$$

Remark that

$$T_l T_r^* \otimes 1 + 1 \otimes T_l T_r^* - T_r^* \otimes T_l - T_l \otimes T_r^* = (T_l \otimes 1 - 1 \otimes T_l)(T_r^* \otimes 1 - 1 \otimes T_r^*),$$

so it is enough to show that  $T_l \otimes 1 - 1 \otimes T_l$  and  $T_r^* \otimes 1 - 1 \otimes T_r^*$  strongly commute with  $\alpha \otimes \alpha$ , which follows from

$$\begin{aligned} e^{i\text{Im}z(T_r^* \otimes 1 - 1 \otimes T_r^*)}(\alpha \otimes \alpha)e^{-i\text{Im}z(T_r^* \otimes 1 - 1 \otimes T_r^*)} &= (\lambda_{0,-\bar{z}} \otimes \lambda_{0,\bar{z}})(\alpha \otimes \alpha)(\lambda_{0,-\bar{z}} \otimes \lambda_{0,\bar{z}})^* \\ &= e^{-\bar{z}}e^{\bar{z}}\alpha \otimes \alpha = \alpha \otimes \alpha, \\ e^{i\text{Im}z(T_l \otimes 1 - 1 \otimes T_l)}(\alpha \otimes \alpha)e^{-i\text{Im}z(T_l \otimes 1 - 1 \otimes T_l)} &= (\lambda_{z,0} \otimes \lambda_{-z,0})(\alpha \otimes \alpha)(\lambda_{z,0} \otimes \lambda_{-z,0})^* \\ &= e^{-z}e^z\alpha \otimes \alpha = \alpha \otimes \alpha. \end{aligned}$$

By definition of  $\hat{\Delta}_x$ , we have

$$\hat{\Delta}_x(\hat{B}) = \hat{\Delta}_x(e^{x\text{Re}T_l}|\beta|) = (e^{x\text{Re}T_l} \otimes 1)\Upsilon|\alpha \otimes \beta + \beta \otimes 1|\Upsilon^*,$$

$$\hat{\Delta}_x(\hat{v}) = \hat{\Delta}_x(e^{-ix\text{Im}T_l}\text{Ph}(\beta)) = (e^{-ix\text{Im}T_l} \otimes 1)\Upsilon\text{Ph}(\alpha \otimes \beta + \beta \otimes 1)\Upsilon^*.$$

A direct computation gives

$$\text{Ph}(\alpha \otimes \beta + \beta \otimes 1)(e^{x\text{Re}T_l} \otimes 1) = e^x(e^{x\text{Re}T_l} \otimes 1)\text{Ph}(\alpha \otimes \beta + \beta \otimes 1),$$

so

$$\begin{aligned} \hat{\Delta}_x(\hat{\beta}) &= e^x(e^{xT_l^*} \otimes 1)\Upsilon(\alpha \otimes \beta + \beta \otimes 1)\Upsilon^* \\ &= e^x(e^{xT_l^*} \otimes 1)\Upsilon(\alpha \otimes \beta)\Upsilon^* + e^x(e^{xT_l^*} \otimes 1)\Upsilon(\beta \otimes 1)\Upsilon^*. \end{aligned}$$

Thus, it suffices to show that

$$\hat{\alpha} \otimes \hat{\beta} = e^x(e^{xT_l^*} \otimes 1)\Upsilon(\alpha \otimes \beta)\Upsilon^* \quad (20)$$

$$\hat{\beta} \otimes 1 = e^x(e^{xT_l^*} \otimes 1)\Upsilon(\beta \otimes 1)\Upsilon^*. \quad (21)$$

Let us prove (20). Let us put  $T = e^x e^{xT_l^*} \otimes 1 = e^x L \otimes 1$  and  $S = \Upsilon(\alpha \otimes \beta)\Upsilon^*$ . We want to show that  $\hat{\alpha} \otimes \hat{\beta} = TS$ . For all  $z \in \mathbb{C}$ , we have

$$e^{ix\text{Im}z(T_r \otimes 1)}(\alpha \otimes 1)e^{-ix\text{Im}z(T_r \otimes 1)} = (\lambda_{0,xz}\alpha\lambda_{0,-xz}^* \otimes 1) = e^{xz}(\alpha \otimes 1),$$

and, using the fact that  $\alpha \otimes 1$  and  $1 \otimes T_l^*$  strongly commute, we obtain  $\Upsilon(\alpha \otimes 1)\Upsilon^* = \alpha \otimes e^{xT_l^*} = \alpha \otimes L$ . Similarly,  $\Upsilon(1 \otimes \beta)\Upsilon^* = R \otimes \beta$ . Thus, using Lemma 14, we see that the polar decomposition of  $S$  is

$$\text{Ph}(S) = \text{Ph}(\alpha)\text{Ph}(R) \otimes \text{Ph}(\beta)\text{Ph}(L), \quad |S| = |\alpha||R| \otimes |\beta||L|.$$

Moreover, the polar decomposition of  $T$  is given by  $\text{Ph}(T) = \text{Ph}(L) \otimes 1$ ,  $|T| = e^x|L| \otimes 1$ , so, using Lemma 14, one can see that  $(T, S)$  is a  $e^x$ -commuting pair. In particular, the polar decomposition of  $TS$  is

$$|TS| = e^{-x}|T||S| = |L||\alpha||R||\beta||L|, \quad \text{Ph}(TS) = \text{Ph}(L)\text{Ph}(\alpha)\text{Ph}(R) \otimes \text{Ph}(\beta)\text{Ph}(L).$$

But Proposition 12 gives  $\text{Ph}(\hat{\alpha}) = \text{Ph}(L)\text{Ph}(R)\text{Ph}(\alpha)$  and  $|\alpha| = |L||R||\alpha|$ . Thus, we conclude that  $\text{Ph}(\hat{\alpha} \otimes \hat{\beta}) = \text{Ph}(TS)$  and  $|\hat{\alpha} \otimes \hat{\beta}| = |TS|$  which concludes the proof of (20). One can prove (21) similarly.  $\blacksquare$

Now the proof of Theorem 3 follows: Proposition 11 says that  $\hat{\alpha}$  and  $\hat{\beta}$  generate  $\widehat{M}_x$  and Proposition 12 gives the commutation relations for  $\hat{\alpha}$  and  $\hat{\beta}$ .

## 5.2 Twisting of the quantum $az + b$ group

This Section is devoted to the proof of Theorem 4. Let  $0 < q < 1$  and  $(M, \Delta)$  be the  $az + b$  Woronowicz' quantum group. Let  $\alpha : L^\infty(\mathbb{C}^q) \rightarrow M$  be defined by  $\alpha(F) = F(a)$ . Recall that (Section 2.7)  $\widehat{\mathbb{C}}^q < (M, \Delta)$  is an abelian stable co-subgroup with the morphism  $\gamma_t = q^{2it} \in \mathbb{C}^q$ . Let us perform the twisting construction using the bicharacters

$$\Psi_x(q^{k+i\varphi}, q^{l+i\psi}) = q^{ix(k\psi-l\varphi)}, \quad \forall x \in \mathbb{Z},$$

and let  $(M_x, \Delta_x)$  be the twisted l.c. quantum group.

### Proposition 14

$$\Delta_x(a) = a \otimes a \quad \text{and} \quad \Delta_x(b) = u^{-x+1}|a|^{x+1} \otimes b \dot{+} b \otimes u^x|a|^{-x},$$

and  $[D\varphi_x : D\varphi]_t = A_x^{it} = |a|^{-2ixt}$ . The modular element  $\delta_x = |a|^{4x+2}$ , the antipode is not deformed. If  $x, y \in \mathbb{N}$  and  $x \neq y$ , then  $(M_x, \Delta_x)$  and  $(M_y, \Delta_y)$  are not isomorphic; if  $x \neq 0$ , then  $(M_x, \Delta_x)$  and  $(M_{-x}, \Delta_{-x})$  are not isomorphic.

**Proof.** The relations of commutation from Preliminaries give

$$\begin{aligned} \Psi_x(a, q^{l+i\psi})b &= \Psi_x(u, q^{l+i\psi})\Psi_x(|a|, q^{l+i\psi})b \\ &= u^{-xl}|a|^{ix\psi}v|b| \\ &= q^{ix\psi-xl}v|b|u^{-xl}|a|^{ix\psi} \\ &= q^{ix\psi-xl}b\Psi_x(a, q^{l+i\psi}). \end{aligned}$$

So, for any  $\gamma \in \mathbb{C}^q$ , one has

$$\Psi_x(a \otimes 1, \gamma)(b \otimes 1)\Psi_x(a \otimes 1, \gamma)^* = (\text{Phase}(\gamma))^x |\gamma|^{-x}(b \otimes 1).$$

Put  $\Omega_x = (\alpha \otimes \alpha)(\Psi_x) = \Psi_x(a \otimes 1, 1 \otimes a)$ . Using the previous formula and the fact that  $b \otimes 1$  and  $1 \otimes a$  strongly commute, one gets  $\Omega_x(b \otimes 1)\Omega_x^* = b \otimes u^x|a|^{-x}$ . Similarly:  $\Omega_x(1 \otimes b)\Omega_x^* = u^{-x}|a|^x \otimes b$ . These formulas give the comultiplication on  $b$ . The comultiplication on  $a$  is clear. We Since  $\Psi_s(\gamma_t, \gamma_s) = 1$ , for all  $s, t \in \mathbb{R}$ , then  $[D\varphi_x : D\varphi]_t = A_x^{it} = \Psi_x(a, \gamma_t^{-1}) = |a|^{-2ixt}$ . Put  $f_t^x = \Psi_x(\cdot, \gamma_t)\Psi_x(\gamma_t^{-1}, \cdot)$ , then  $f_t^x(q^{k+i\varphi}) = q^{4itxk}$  and  $\alpha(f_t^x) = |a|^{4itx}$ . So, the modular element is  $\delta_x = |a|^2|a|^{4x}$ . The antipode is not deformed because  $\Psi_t(x^{-1}, x) = 1$ , for any  $x$ . The spectrum of the modular element is  $\text{Sp}(\delta_x) = q_x^{\mathbb{Z}} \cup \{0\}$ , where  $q_x = q^{4x+2}$ , so, if  $x \neq y$  are strictly positive, then  $0 < q_x \neq q_y < 1$ , so  $q_x^{\mathbb{Z}} \neq q_y^{\mathbb{Z}}$ , then

$(M_x, \Delta_x)$  and  $(M_y, \Delta_y)$  are not isomorphic. Moreover, if  $x > 0$ , then  $(M_x, \Delta_x)$  is not isomorphic to  $(M_{-x}, \Delta_{-x})$  because in the opposite case we would have  $q^{(4x+2)\mathbb{Z}} = q^{(4x-2)\mathbb{Z}}$ , from where, as  $x > 0$ ,  $4x + 2 = 4x - 2$  - contradiction. ■

The group  $\mathbb{C}^q$  is selfdual with the duality  $(q^{k+i\varphi}, q^{l+i\psi}) \mapsto q^{i(k\psi+l\varphi)}$ , so one can compute the representations  $L$  and  $R$  of  $\mathbb{C}^q$ :

$$L_{q^{k+i\varphi}} = m^{i\varphi} \otimes s^{-k} \otimes 1 \otimes s^k, \quad R_{q^{k+i\varphi}} = m^{-i\varphi} \otimes 1 \otimes m^{i\varphi} \otimes s^{-k}.$$

Then the left-right action of  $(\mathbb{C}^q)^2$  on the generators of  $\widehat{M}$  is

$$\alpha_{q^{k+i\varphi}, q^{l+i\psi}}(\hat{a}) = q^{l-k+i(\psi-\varphi)}\hat{a}, \quad \alpha_{q^{k+i\varphi}, q^{l+i\psi}}(\hat{b}) = q^{-k-i\varphi}\hat{b}. \quad (22)$$

Let  $N = (\mathbb{C}^q)^2 \rtimes \widehat{M}$ , it is generated by the operators  $\lambda_{q^{k+i\varphi}, q^{l+i\psi}}$  and  $\pi(x)$ , for  $x \in \widehat{M}$ , and  $\theta$  be the dual action of  $(\mathbb{C}^q)^2$  on  $N$ . The deformed dual action is

$$\theta_{q^{k+i\varphi}, q^{l+i\psi}}^{\Psi_x} = \lambda_{q^{x(k-i\varphi)}, q^{x(-l+i\psi)}} \theta_{q^{k+i\varphi}, q^{l+i\psi}}(\cdot) \lambda_{q^{x(k-i\varphi)}, q^{x(-l+i\psi)}}^*.$$

Let  $\widehat{M}_x$  be the fixed point algebra. The left-right action is very similar to the one for the classical  $az + b$ . Define  $\alpha = \pi(\hat{a})$ ,  $\beta = \pi(\hat{b})$ . Then  $\alpha$  and  $\beta$  are normal operators affiliated with  $N$  and one can see that

$$\theta_{q^{k+i\varphi}, q^{l+i\psi}}^{\Psi_x}(\alpha) = q^{-x(l+k)+ix(\varphi+\psi)}\alpha, \quad \theta_{q^{k+i\varphi}, q^{l+i\psi}}^{\Psi_x}(\beta) = q^{-xk+ix\varphi}\beta. \quad (23)$$

Let  $T_l$  and  $T_r$  be the "infinitesimal generators" of the left and right translations, so  $T_l$  and  $T_r$  are affiliated with  $N$  and

$$\lambda_{q^{k+i\varphi}, q^{l+i\psi}} = (\text{Ph}T_l)^k |T_l|^{i\varphi} (\text{Ph}T_r)^l |T_r|^{i\psi}. \quad (24)$$

Then  $\lambda(f) = f(T_l, T_r) \forall f \in L^\infty((\mathbb{C}^q)^2)$ . Let  $U = \lambda(\Psi_x)$  and  $\hat{\alpha} = U^* \alpha U$ .

**Proposition 15**  $(T_l^* T_r^*)^{-x}$  and  $\alpha$  strongly commute and  $\hat{\alpha} = (T_l^* T_r^*)^{-x} \alpha$ . The polar decomposition of  $\hat{\alpha}$  is  $\hat{\alpha} := \text{Ph}\hat{\alpha} = (\text{Ph}T_l T_r)^x$ ,  $\hat{A} := |\hat{\alpha}| = |T_l T_r|^{-x} |\alpha|$ . Also,  $|T_l|$  and  $|\beta|$  strongly commute, so we can define a positive operator  $\hat{B} = |T_l|^{-x} |\beta|$ . Let  $\hat{v} = \text{Ph}(T_l)^x \text{Ph}(\beta)$ . Then  $\hat{\alpha}$  and  $\hat{B}$  are affiliated with  $\widehat{M}_x$ ,  $\hat{v} \in \widehat{M}_x$ , and we have the following relations of commutation:

- $\hat{v}\hat{v} = \hat{v}\hat{v}$ ,  $\hat{A}\hat{B} = \hat{B}\hat{A}$ ;
- $\hat{v}\hat{B}\hat{v}^* = q^{-2x}\hat{B}$ ,  $\hat{v}\hat{B}\hat{v}^* = q^{-2x+1}\hat{B}$  and,  $\hat{v}\hat{A}\hat{v}^* = q^{-2x-1}\hat{A}$ .

Moreover, these three operators generate  $\widehat{M}_x$  in the sense that

$$\widehat{M}_x = \left\{ f(\hat{\alpha})g(\hat{v})h(\hat{B}), f \in L^\infty(\mathbb{C}^q), g \in L^\infty(\mathbb{S}^1), h \in L^\infty(q^{\mathbb{Z}}) \right\}''.$$

**Proof.** Using (22) and (24), we find:

$$|T_l T_r|^{is} \alpha |T_l T_r|^{-is} = \alpha, \quad (25)$$

$$\text{Ph}(T_l T_r) \alpha \text{Ph}(T_l T_r)^* = \alpha, \quad (26)$$

$$|T_l|^{is} \beta |T_l|^{-is} = q^{-is} \beta, \quad (27)$$

$$\text{Ph}(T_l) \beta \text{Ph}(T_l)^* = q^{-1} \beta. \quad (28)$$

Due to (25) and (26),  $\alpha$  and  $T_l^* T_r^*$  strongly commute. Because  $\Psi_x(T_r, T_r) = 1$ , we have  $\hat{\alpha} = \Psi_x(T_l T_r, T_r)^* \alpha \Psi_x(T_l T_r, T_r)$ . Next, using  $\Psi_x(q^{k+i\varphi}, T_r)^* \alpha \Psi_x(q^{k+i\varphi}, T_r) = \lambda_{1, q^{-xk+i\varphi}} \alpha \lambda_{1, q^{-xk+i\varphi}}^* = q^{-xk+i\varphi} \alpha$ , and because  $T_l T_r$  and  $\alpha$  strongly commute, we have

$$\hat{\alpha} = |T_l T_r|^{-x} (\text{Ph} T_l T_r)^x \alpha = (T_l^* T_r^*)^{-x} \alpha.$$

The polar decomposition of  $\hat{\alpha}$  follows. Equality (27) implies that  $|T_l|$  and  $|\beta|$  strongly commute. Note that

$$\begin{aligned} \theta_{q^{k+i\varphi}, q^{l+i\psi}}^{\Psi_x}(U) &= \Psi_x(T_l q^{-k-i\varphi}, T_r q^{-l-i\psi}) \\ &= U \lambda_{q^{x l - i x \psi}, q^{-x k + i x \varphi}} \Psi_x(q^{k+i\varphi}, q^{l+i\psi}). \end{aligned}$$

Then, it follows from (22) and (23) that  $\hat{\alpha}$  is affiliated with  $\widehat{M}_x$ . Also, using (23) we find  $\theta_{q^{k+i\varphi}, q^{l+i\psi}}^{\Psi_x}(\hat{v}) = (\text{Ph}(T_l q^{-k-i\varphi}))^x q^{ix\varphi} \text{Ph} \beta = \hat{v}$ , so  $\hat{v} \in \widehat{M}_x$ . In the same way we prove that  $\hat{B}$  is affiliated with  $\widehat{M}_x$ . It is easy to see that  $\text{Ph} T_l$  and  $\text{Ph} T_r$  commute with  $\text{Ph} \alpha$  and  $\text{Ph} \beta$ , and because  $\text{Ph} \alpha$  and  $\text{Ph} \beta$  commute, it follows that  $\hat{u} \hat{v} = \hat{v} \hat{u}$ . Also,  $|T_l|$  and  $|T_r|$  strongly commute with  $|\alpha|$  and  $|\beta|$ , and because  $|\alpha|$  and  $|\beta|$  strongly commute, it follows that  $\hat{A} \hat{B} = \hat{B} \hat{A}$ . The relation  $\hat{v} \hat{B} \hat{v}^* = q^{-2x} \hat{B}$  follows from (27) and (28). Remark that

$$\text{Ph} \alpha |T_l|^{-x} \text{Ph} \alpha^* = q^{-x} |T_l|^{-x}, \quad \text{Ph} \beta |T_l T_r|^{-x} \text{Ph} \beta^* = q^{-x} |T_l T_r|^{-x},$$

and the two last relations follow from  $\text{Ph} \alpha |\beta| \text{Ph} \alpha^* = q |\beta|$  and  $\text{Ph} \beta |\alpha| \text{Ph} \beta^* = q^{-1} |\beta|$ . The generating property is proved as in Proposition 11.  $\blacksquare$

Let  $\hat{\Delta}_x$  be the comultiplication on  $\widehat{M}_x$  and  $\hat{\beta} = \hat{v} \hat{B}$ . Then  $\hat{\beta}$  is a closed (non-normal) operator affiliated with  $\widehat{M}_x$ . As before, we define  $\hat{\Delta}_x(\hat{\beta}) = \hat{\Delta}_x(\hat{v}) \hat{\Delta}_x(\hat{B})$  which is closed, non-normal and affiliated with  $\widehat{M}_x \otimes \widehat{M}_x$ . The proof of the following Proposition is similar to the one of Proposition 13.

**Proposition 16**

$$\hat{\Delta}_x(\hat{\alpha}) = \hat{\alpha} \otimes \hat{\alpha} \quad \text{and} \quad \hat{\Delta}_x(\hat{\beta}) = \hat{\alpha} \otimes \hat{\beta} \dot{+} \hat{\beta} \otimes 1.$$

The proof of Theorem 4 follows from the results of this section.

## 6 Appendix

Let  $\alpha$  be an action of a l.c. quantum group  $(M, \Delta)$  on the von Neumann algebra  $N$ . Let  $\theta$  be a n.s.f. weight on  $N$  and suppose that  $N$  acts on a Hilbert space  $K$  such that  $(K, \iota, \Lambda_\theta)$  is the G.N.S. construction for  $\theta$ . We define

$$\mathcal{D}_0 = \text{span}\{(a \otimes 1)\alpha(x) \mid a \in \mathcal{N}_{\hat{\varphi}}, x \in \mathcal{N}_\theta\}.$$

Let  $(H, \iota, \Lambda)$  be the G.N.S. construction for the left invariant weight  $\varphi$  of  $(M, \Delta)$ ,  $\hat{\varphi}$  the dual weight, and  $\hat{\Lambda}$  its canonical G.N.S.-map. We recall that the G.N.S. construction for the dual weight  $\hat{\theta}$  is given by  $(H \otimes K, \iota, \hat{\Lambda})$ , where  $\hat{\Lambda}_\theta$  is the  $\sigma$ -strong\*-norm closure of the map

$$\mathcal{D}_0 \rightarrow H \otimes K : (a \otimes 1)\alpha(x) \mapsto \hat{\Lambda}(a) \otimes \Lambda_\theta(x).$$

**Proposition 17** *Let  $C_1$  be a  $\sigma$ -strong\*-norm core for  $\hat{\Lambda}$  and  $C_2$  a  $\sigma$ -strong\*-norm core for  $\Lambda_\theta$ . Then the set  $\mathcal{C} = \text{span}\{(a \otimes 1)\alpha(x) \mid a \in C_1, x \in C_2\}$  is a  $\sigma$ -weak-weak core for  $\hat{\Lambda}_\theta$ .*

**Proof.** Let  $a \in \mathcal{N}_{\hat{\varphi}}$  and  $x \in \mathcal{N}_\theta$ . There exists two nets  $(a_i)$  and  $(x_i)$ , with  $a_i \in C_1$  and  $x_i \in C_2$ , such that

$$a_i \rightarrow a, x_i \rightarrow x \quad \sigma\text{-strongly}^* \quad \text{and} \quad \hat{\Lambda}(a_i) \rightarrow \hat{\Lambda}(a), \Lambda_\theta(x_i) \rightarrow \Lambda_\theta(x).$$

Thus,  $(a_i \otimes 1)\alpha(x_i) \rightarrow (a \otimes 1)\alpha(x)$   $\sigma$ -weakly and

$$\tilde{\Lambda}_\theta((a_i \otimes 1)\alpha(x_i)) = \hat{\Lambda}(a_i) \otimes \Lambda_\theta(x_i) \rightarrow \hat{\Lambda}(a) \otimes \Lambda_\theta(x) = \tilde{\Lambda}_\theta((a \otimes 1)\alpha(x)).$$

■

**Proposition 18** *Let  $M$  be a von Neumann algebra with a n.s.f. weight  $\varphi$ ,  $(H, \iota, \Lambda)$  the G.N.S. construction for  $\varphi$ , and  $T$  a positive self-adjoint operator affiliated with  $M$ . Then  $\mathcal{C} = \{x \in \mathcal{N}_\varphi \mid Tx \text{ is bounded and } \Lambda(x) \in \mathcal{D}(T)\}$  is a  $\sigma$ -strong\*-norm core for  $\Lambda$  and, if  $x \in \mathcal{C}$ , then  $\overline{Tx} \in \mathcal{N}_\varphi$  and  $\Lambda(\overline{Tx}) = T\Lambda(x)$ .*

**Proof.** Let  $T = \int_0^{+\infty} \lambda de_\lambda$  be the spectral decomposition of  $T$ . Let  $e_n = \int_0^n de_\lambda$ . Then  $e_n \rightarrow 1$   $\sigma$ -strongly\*,  $Te_n$  is bounded with domain  $H$ . Let  $x \in \mathcal{N}_\varphi$  and put  $x_n = e_n x$ . We have  $x_n \rightarrow x$   $\sigma$ -strongly\* and  $\Lambda(x_n) = e_n \Lambda(x) \rightarrow \Lambda(x)$  in norm. Moreover,  $Tx_n = Te_n x$  is bounded and  $\Lambda(x_n) = e_n \Lambda(x) \in \mathcal{D}(T)$ , so  $x_n \in \mathcal{C}$ , and it follows that  $\mathcal{C}$  is a  $\sigma$ -strong\*-norm core for  $\Lambda$ . Now let  $x \in \mathcal{C}$ . Note that  $e_n \overline{Tx} = Te_n x = \overline{e_n Tx}$  is in  $\mathcal{N}_\varphi$  and it converges  $\sigma$ -strongly\* to  $\overline{Tx}$ . Moreover,

$$\Lambda(e_n \overline{Tx}) = \overline{e_n T \Lambda(x)} = e_n T \Lambda(x) \rightarrow T \Lambda(x).$$

Because  $\Lambda$  is  $\sigma$ -strong\*-norm closed, we have  $\overline{Tx} \in \mathcal{N}_\varphi$  and  $\Lambda(\overline{Tx}) = T\Lambda(x)$ . ■

**Proposition 19** *Let  $M$  be a von Neumann algebra,  $\varphi_1$  and  $\varphi_2$  two n.s.f. weights on  $M$  having the same modular group. Let  $(H_i, \pi_i, \Lambda_i)$  be the G.N.S. construction for  $\varphi_i$  ( $i = 1, 2$ ). Suppose that there exist a  $\sigma$ -weak-weak core  $\mathcal{C}$  for  $\Lambda_1$  such that  $\mathcal{C} \subset \mathcal{N}_{\varphi_1} \cap \mathcal{N}_{\varphi_2}$  and a unitary  $Z : H_1 \rightarrow H_2$  such that  $\Lambda_2(x) = Z\Lambda_1(x)$ , for all  $x \in \mathcal{C}$ . Then  $\varphi_1 = \varphi_2$ .*

**Proof.** Because  $\mathcal{C}$  is a  $\sigma$ -weak-weak core for  $\Lambda_1$  and because  $\Lambda_2$  is  $\sigma$ -weak-weak closed, we have  $\mathcal{N}_{\varphi_1} \subset \mathcal{N}_{\varphi_2}$  and, for all  $x \in \mathcal{N}_{\varphi_1}$  we have  $\Lambda_1(x) = Z\Lambda_2(x)$ . Thus,  $\varphi_1(y^*x) = \varphi_2(y^*x)$ , for all  $x, y \in \mathcal{N}_{\varphi_1}$ . Let  $\mathcal{B} = \mathcal{N}_{\varphi_1}^* \mathcal{N}_{\varphi_1}$ . This is a dense \*-subalgebra of  $\mathcal{M}_{\varphi_1} \cap \mathcal{M}_{\varphi_2}$  and, for all  $x \in \mathcal{B}$ , we have  $\varphi_1(x) = \varphi_2(x)$ . Because  $\varphi_1$  and  $\varphi_2$  have the same modular group, we can use the Pedersen-Takesaki Theorem [13] to conclude the proof. ■

Let  $M$  be a von Neumann algebra,  $\varphi$  a n.s.f. weight on  $M$ ,  $(H, \iota, \Lambda)$  the G.N.S. construction for  $\varphi$ , and  $\sigma$  the modular group of  $\varphi$ . Let  $\delta$  be a positive self-adjoint operator affiliated with  $M$ ,  $\lambda > 0$  such that  $\sigma_t(\delta^{is}) = \lambda^{ist} \delta^{is}$ , and  $\Lambda_\delta$  the canonical G.N.S. map of the Vaes' weight  $\varphi_\delta$ . One can consider on  $M \otimes M$  two n.s.f. weights:  $\varphi_\delta \otimes \varphi_\delta$ , with the canonical G.N.S. map  $\Lambda_\delta \otimes \Lambda_\delta$ , and the Vaes' weight  $(\varphi \otimes \varphi)_{\delta \otimes \delta}$  associated with  $\varphi \otimes \varphi$ ,  $\delta \otimes \delta$  and  $\lambda^2$ . Let  $\Lambda \otimes \Lambda$  be the G.N.S. map for  $\varphi \otimes \varphi$ , and  $(\Lambda \otimes \Lambda)_{\delta \otimes \delta}$  the G.N.S. map for  $(\varphi \otimes \varphi)_{\delta \otimes \delta}$  (see Section 2.6).

**Proposition 20**  $\varphi_\delta \otimes \varphi_\delta = (\varphi \otimes \varphi)_{\delta \otimes \delta}$  and  $\Lambda_\delta \otimes \Lambda_\delta = (\Lambda \otimes \Lambda)_{\delta \otimes \delta}$ .

**Proof.** Let us apply the Pedersen-Takesaki theorem to the weights  $\varphi_1 := (\varphi_\delta \otimes \varphi_\delta)$  and  $\varphi_2 := (\varphi \otimes \varphi)_{\delta \otimes \delta}$  which have the same modular group and are equal on the dense \*-subalgebra  $\mathcal{B} = N \odot N$  of  $\mathcal{M}_{\varphi_1} \cap \mathcal{M}_{\varphi_2}$ , where

$$N := \left\{ x \in M \mid x\delta^{\frac{1}{2}} \text{ is bounded and } \overline{x\delta^{\frac{1}{2}}} \in \mathcal{N}_\varphi \right\}.$$

Let  $\Lambda_i$  be the canonical G.N.S. map of  $\varphi_i$ . By definition,  $N \odot N$  is a  $\sigma$ -strong\*-norm core for  $\Lambda_1$ , and  $\Lambda_1|_N = \Lambda_2|_N$ . Since  $\Lambda_1$  and  $\Lambda_2$  are  $\sigma$ -strongly\*-norm closed, then  $\Lambda_1 \subset \Lambda_2$ . And  $\Lambda_1 = \Lambda_2$  since  $\mathcal{D}(\Lambda_1) = \mathcal{N}_{\varphi_1} = \mathcal{N}_{\varphi_2} = \mathcal{D}(\Lambda_2)$ . ■

Finally, let us formulate the von Neumann algebraic version of [6], Lemma 3.6. Let  $N$  be a von Neumann algebra,  $G$  a l.c. abelian group,  $u : G \rightarrow N$  a unitary representation of  $G$  and  $\theta : \hat{G} \rightarrow \text{Aut}(N)$  an action of  $\hat{G}$  on  $N$  such that

$$\theta_\gamma(u(g)) = \overline{\langle \gamma, g \rangle} u(g).$$

Let  $\alpha$  be the action of  $G$  on  $N$  implemented by  $u$ . The unitary representation  $u$  of  $G$  gives a \*-homomorphism  $\pi : L^\infty(\hat{G}) \rightarrow N$ .

**Lemma 15** *Let  $V$  be a linear subspace of  $N^\theta$  invariant under the action  $\alpha$  and such that  $\left( \pi(L^\infty(\hat{G}))V\pi(L^\infty(\hat{G})) \right)'' = N$ . Then  $V'' = N^\theta$ .*

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