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**MEAN ERGODIC THEOREM FOR AMENABLE DISCRETE
QUANTUM GROUPS AND A WIENER-TYPE THEOREM FOR
COMPACT METRIZABLE GROUPS**

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We prove a mean ergodic theorem for amenable discrete quantum groups. As an application, we prove a Wiener-type theorem for continuous measures on compact metrizable groups.

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1. Introduction

A countable discrete group Γ is called *amenable* if there exists a sequence $\{F_n\}_{n=1}^\infty$ (called a right Følner sequence) consisting of finite subsets F_n of Γ such that

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|} |F_n s \Delta F_n| = 0$$

for every $s \in \Gamma$.

Let $(X, \mathcal{B}, \mu, \Gamma)$ be a dynamical system consisting of a countable discrete amenable group Γ with a measure-preserving action on a probability space (X, \mathcal{B}, μ) .

Recall that von Neumann's mean ergodic theorem for amenable group actions on measure spaces says the following:

Theorem 1.1 (measure space version of von Neumann's mean ergodic theorem [Glasner 2003, Theorem 3.33]). *Let $\{F_n\}_{n=1}^\infty$ be a right Følner sequence of Γ . Then, for every $f \in L^2(X, \mu)$, the sequence $(1/|F_n|) \sum_{s \in F_n} s \cdot f$ converges to Pf with respect to the L^2 norm, where P is the orthogonal projection from $L^2(X, \mu)$ onto the space $\{g \in L^2(X, \mu) \mid s \cdot g = g \text{ for all } s \in \Gamma\}$.*

R. Duvenhage [2008, Theorem 3.1] proves a generalization of von Neumann's mean ergodic theorem for coactions of amenable quantum groups on von Neumann algebras (noncommutative measure spaces). Later, a more general version was proved by V. Runge and A. Viselter [2014, Theorem 2.2].

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There is also a version of von Neumann’s mean ergodic theorem for amenable group actions on Hilbert spaces, which says the following:

Theorem 1.2 (Hilbert space version of von Neumann’s mean ergodic theorem). *Let $\{F_n\}_{n=1}^\infty$ be a right Følner sequence of a countable discrete amenable group Γ and $\pi : \Gamma \rightarrow B(H)$ be a unitary representation of Γ on a Hilbert space H . Set $H_\Gamma = \{x \in H \mid \pi(s)x = x \text{ for all } s \in \Gamma\}$. Then*

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|} \sum_{s \in F_n} \pi(s) = P$$

under the strong operator topology on $B(H)$, where P is the orthogonal projection from H onto H_Γ .

The group C^* -algebra $C^*(\Gamma)$ equals $C(G)$ for a coamenable compact quantum group G with the dual group $\widehat{G} = \Gamma$. The counit ε of G is given by $\varepsilon(\delta_s) = 1$ for all $s \in \Gamma$. Hence,

$$H_\Gamma = \{x \in H \mid \pi(a)x = \varepsilon(a)x \text{ for all } a \in C^*(\Gamma)\}.$$

With these in mind, the Hilbert space version of von Neumann’s mean ergodic theorem can be reformulated in the framework of compact quantum groups as follows.

Suppose G is a coamenable compact quantum group such that the dual \widehat{G} is a countable discrete amenable group Γ . Let $\{F_n\}_{n=1}^\infty$ be a right Følner sequence of Γ and $\pi : C(G) = C^*(\Gamma) \rightarrow B(H)$ be a representation of $C^*(\Gamma)$ on a Hilbert space H . Then

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|} \sum_{s \in F_n} \pi(s) = P$$

under the strong operator topology on $B(H)$, where P is the orthogonal projection from H onto $H_\Gamma = \{x \in H \mid \pi(a)x = \varepsilon(a)x \text{ for all } a \in C^*(\Gamma)\}$.

D. Kyed proves that a compact quantum group G is coamenable if and only if there exists a right Følner sequence $\{F_n\}_{n=1}^\infty$ of finite subsets in its dual \widehat{G} , that is to say, G is a coamenable compact quantum group if and only if \widehat{G} is an amenable discrete quantum group [2008, Definition 4.9.].¹ So it is natural to ask for a generalization of the Hilbert space version of von Neumann’s mean ergodic theorem to all amenable discrete quantum groups. This is the main result of the paper.

Theorem 3.1 (mean ergodic theorem for amenable discrete quantum groups). *Let G be a coamenable compact quantum group with counit ε and let $\{F_n\}_{n=1}^\infty$ be a right Følner sequence of \widehat{G} . Set $H_{\text{inv}} = \{x \in H \mid \pi(a)x = \varepsilon(a)x \text{ for all } a \in A\}$. For a representation $\pi : A = C(G) \rightarrow B(H)$, we have*

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \pi(\chi(\alpha)) = P \tag{1-1}$$

under the strong operator topology, where P is the orthogonal projection from H onto H_{inv} .

¹The existence of a Følner sequence for Kac-type compact quantum groups is shown by Z. Ruan [1996]. Also see [Tomatsu 2006].

Here $|F_n|_w$ stands for the weighted cardinality of F_n . Definitions of $|F_n|_w$, d_α and $\chi(\alpha)$ are in Section 2.

The left-hand side of (1-1) involves both a representation of a coamenable compact quantum group G and that of its discrete quantum group dual \widehat{G} , so it illustrates some interactions between them.

The rest of the paper aims at an application of Theorem 3.1. Namely, we prove a Wiener-type theorem for finite Borel measures on compact metrizable groups.

A finite Borel measure μ on a compact metrizable space X is called *continuous* or *nonatomic* if $\mu\{x\} = 0$ for every $x \in X$.

The following theorem of N. Wiener [1933] expresses finite Borel measures on the unit circle via their Fourier coefficients.

Theorem 1.3 (Wiener’s theorem [Katznelson 2004, Chapter 1, Theorem 7.13]). *For a finite Borel measure μ on the unit circle \mathbb{T} and every $z \in \mathbb{T}$, one has*

$$\lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{n=-N}^N \widehat{\mu}(n)z^{-n} = \mu\{z\} \quad \text{and} \quad \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{n=-N}^N |\widehat{\mu}(n)|^2 = \sum_{x \in \mathbb{T}} \mu\{x\}^2.$$

Hence, μ is continuous if and only if

$$\lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{n=-N}^N |\widehat{\mu}(n)|^2 = 0,$$

where $\widehat{\mu}(n) := \int_{\mathbb{T}} z^n d\mu(z)$ for $n \in \mathbb{Z}$ are the Fourier coefficients of μ .

There are various generalized Wiener’s theorems (we call such generalizations Wiener-type theorems), including a version for compact manifolds [Taylor 1981, Chapter XII, Theorem 5.1], a version for compact Lie groups by M. Anoussis and A. Bisbas [2000, Theorem 7], and a version for compact homogeneous manifolds by M. Björklund and A. Fish [2009, Lemma 2.1].

We apply the above mean ergodic theorem (Theorem 3.1) to get a Wiener-type theorem on compact metrizable groups. This version differs from previous ones mainly in two aspects: firstly we don’t require smoothness on spaces; secondly we use a different Følner condition.

Theorem 4.1 (Wiener-type theorem for compact metrizable groups). *Let G be a compact metrizable group. Given y in G and a right Følner sequence $\{F_n\}_{n=1}^\infty$ of \widehat{G} , for a finite Borel measure μ on G one has*

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \sum_{1 \leq i, j \leq d_\alpha} \mu(u_{ij}^\alpha) \overline{\mu(u_{ij}^\alpha(y))} = \mu\{y\} \quad \text{and} \quad \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \sum_{1 \leq i, j \leq d_\alpha} |\mu(u_{ij}^\alpha)|^2 = \sum_{x \in G} \mu\{x\}^2.$$

Hence, μ is continuous if and only if

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \sum_{1 \leq i, j \leq d_\alpha} |\mu(u_{ij}^\alpha)|^2 = 0.$$

Here the u_{ij}^α are the matrix coefficients of the irreducible unitary representation α of G ; see Section 2 for the precise definition.

The paper is organized as follows.

In Section 2, we collect some basic facts in compact quantum group theory. In Section 3, we prove the mean ergodic theorem, i.e., Theorem 3.1. As a consequence, we obtain Corollary 3.7, which is used in Section 4 to prove Theorem 4.1.

2. Preliminaries

Conventions. Within this paper, we use $B(H, K)$ to denote the space of bounded linear operators from a Hilbert space H to another Hilbert space K , and $B(H)$ stands for $B(H, H)$.

A net $\{T_\lambda\} \subset B(H)$ converges to $T \in B(H)$ under the strong operator topology (SOT) if $T_\lambda x \rightarrow Tx$ for every $x \in H$, and $\{T_\lambda\}$ converges to $T \in B(H)$ under the weak operator topology (WOT) if $\langle T_\lambda x, y \rangle \rightarrow \langle Tx, y \rangle$ for all $x, y \in H$.

The notation $A \otimes B$ always means the minimal tensor product of two C^* -algebras A and B .

For a state φ on a unital C^* -algebra A , we use $L^2(A, \varphi)$ to denote the Hilbert space of Gelfand–Neimark–Segal (GNS) representations of A with respect to φ . The image of $a \in A$ in $L^2(A, \varphi)$ is denoted by \hat{a} .

In this paper all C^* -algebras are assumed to be unital and separable.

Some facts about compact quantum groups. Compact quantum groups are noncommutative analogues of compact groups. They were introduced by S. L. Woronowicz [1987; 1998].

Definition 2.1. A compact quantum group is a pair (A, Δ) consisting of a unital C^* -algebra A and a unital $*$ -homomorphism

$$\Delta : A \rightarrow A \otimes A$$

such that

- (1) $(\text{id} \otimes \Delta)\Delta = (\Delta \otimes \text{id})\Delta$;
- (2) $\Delta(A)(1 \otimes A)$ and $\Delta(A)(A \otimes 1)$ are dense in $A \otimes A$.

One may think of A as $C(G)$, the C^* -algebra of continuous functions on a compact quantum space G with a quantum group structure. In the rest of the paper we write a compact quantum group (A, Δ) as G . The $*$ -homomorphism Δ is called the *coproduct* of G .

There exists a unique state h on A such that

$$(h \otimes \text{id})\Delta(a) = (\text{id} \otimes h)\Delta(a) = h(a)1_A$$

for all a in A . The state h is called the *Haar measure* of G . Throughout this paper, we use h to denote it.

For a compact quantum group G , there is a unique dense unital $*$ -subalgebra \mathcal{A} of A such that:

- (1) Δ maps from \mathcal{A} to $\mathcal{A} \odot \mathcal{A}$ (the algebraic tensor product).
- (2) There exists a unique multiplicative linear functional $\varepsilon : \mathcal{A} \rightarrow \mathbb{C}$ and a linear map $\kappa : \mathcal{A} \rightarrow \mathcal{A}$ such that $(\varepsilon \otimes \text{id})\Delta(a) = (\text{id} \otimes \varepsilon)\Delta(a) = a$ and $m(\kappa \otimes \text{id})\Delta(a) = m(\text{id} \otimes \kappa)\Delta(a) = \varepsilon(a)1$ for all $a \in \mathcal{A}$, where $m : \mathcal{A} \odot \mathcal{A} \rightarrow \mathcal{A}$ is the multiplication map. The functional ε is called the *counit* and κ the *coinverse* of $C(G)$.

Note that ε is only densely defined and not necessarily bounded. If ε is bounded and h is faithful ($h(a^*a) = 0$ implies $a = 0$), then G is called *coamenable* [Bédos et al. 2001]. Examples of coamenable compact quantum groups include $C(G)$ for a compact group G and $C^*(\Gamma)$ for a discrete amenable group Γ .

A nondegenerate (unitary) *representation* U of a compact quantum group G is an invertible (unitary) element in $M(K(H) \otimes A)$ for some Hilbert space H satisfying that $U_{12}U_{13} = (\text{id} \otimes \Delta)U$. Here $K(H)$ is the C^* -algebra of compact operators on H and $M(K(H) \otimes A)$ is the multiplier C^* -algebra of $K(H) \otimes A$.

We write U_{12} and U_{13} , respectively, for the images of U by two maps from $M(K(H) \otimes A)$ to $M(K(H) \otimes A \otimes A)$, where the first one is obtained by extending the map $x \mapsto x \otimes 1$ from $K(H) \otimes A$ to $K(H) \otimes A \otimes A$, and the second one is obtained by composing this map with the flip on the last two factors. The Hilbert space H is called the *carrier Hilbert space* of U . From now on, we always assume representations are nondegenerate. If the carrier Hilbert space H is of finite dimension, then U is called a finite-dimensional representation of G .

For two representations U_1 and U_2 with the carrier Hilbert spaces H_1 and H_2 , respectively, the set of *intertwiners* between U_1 and U_2 , $\text{Mor}(U_1, U_2)$, is defined by

$$\text{Mor}(U_1, U_2) = \{T \in B(H_1, H_2) \mid (T \otimes 1)U_1 = U_2(T \otimes 1)\}.$$

Two representations U_1 and U_2 are equivalent if there exists a bijection T in $\text{Mor}(U_1, U_2)$. A representation U is called *irreducible* if $\text{Mor}(U, U) \cong \mathbb{C}$.

Moreover, we have the following well-established facts about representations of compact quantum groups:

- (1) Every finite-dimensional representation is equivalent to a unitary representation.
- (2) Every irreducible representation is finite-dimensional.

Let \widehat{G} be the set of equivalence classes of irreducible unitary representations of G . For every $\gamma \in \widehat{G}$, let $U^\gamma \in \gamma$ be unitary and H_γ be its carrier Hilbert space with dimension d_γ . After fixing an orthonormal basis of H_γ , we can write U^γ as $(u_{ij}^\gamma)_{1 \leq i, j \leq d_\gamma}$ with $u_{ij}^\gamma \in A$, and

$$\Delta(u_{ij}^\gamma) = \sum_{k=1}^{d_\gamma} u_{ik}^\gamma \otimes u_{kj}^\gamma$$

for all $1 \leq i, j \leq d_\gamma$.

The matrix \overline{U}^γ is still an irreducible representation (not necessarily unitary) with the carrier Hilbert space \overline{H}_γ . It is called the *conjugate* representation of U^γ and the equivalence class of \overline{U}^γ is denoted by $\overline{\gamma}$.

Given two finite-dimensional representations α and β of G , fix orthonormal bases for α and β and write α and β as U^α and U^β in matrix forms, respectively. Define the *direct sum*, denoted by $\alpha + \beta$, as the equivalence class of unitary representations of dimension $d_\alpha + d_\beta$ given by

$$\begin{pmatrix} U^\alpha & 0 \\ 0 & U^\beta \end{pmatrix},$$

and the *tensor product*, denoted by $\alpha\beta$, is the equivalence class of unitary representations of dimension $d_\alpha d_\beta$ whose matrix form is given by $U^{\alpha\beta} = U_{13}^\alpha U_{23}^\beta$.

The *character* $\chi(\alpha)$ of a finite-dimensional representation α is given by

$$\chi(\alpha) = \sum_{i=1}^{d_\alpha} u_{ii}^\alpha.$$

Note that $\chi(\alpha)$ is independent of the choice of representatives of α . Also we have $\|\chi(\alpha)\| \leq d_\alpha$, since $\sum_{k=1}^{d_\alpha} u_{ik}^\alpha (u_{ik}^\alpha)^* = 1$ for every $1 \leq i \leq d_\alpha$. Moreover,

$$\chi(\alpha + \beta) = \chi(\alpha) + \chi(\beta), \quad \chi(\alpha\beta) = \chi(\alpha)\chi(\beta) \quad \text{and} \quad \chi(\alpha)^* = \chi(\bar{\alpha})$$

for finite-dimensional representations α and β .

Every representation of a compact quantum group is a direct sum of irreducible representations. For two finite-dimensional representations α and β , denote by $N_{\alpha,\beta}^\gamma$ the number of copies of $\gamma \in \widehat{G}$ in the decomposition of $\alpha\beta$ into a sum of irreducible representations. Hence,

$$\alpha\beta = \sum_{\gamma \in \widehat{G}} N_{\alpha,\beta}^\gamma \gamma.$$

We have the Frobenius reciprocity law [Woronowicz 1987, Proposition 3.4; Kyed 2008, Example 2.3]

$$N_{\alpha,\beta}^\gamma = N_{\gamma,\bar{\beta}}^\alpha = N_{\bar{\alpha},\gamma}^\beta$$

for all $\alpha, \beta, \gamma \in \widehat{G}$.

Throughout, we assume that $A = C(G)$ is a separable C^* -algebra, which amounts to saying \widehat{G} is countable.

Definition 2.2 [Kyed 2008, Definition 3.2]. Given two finite subsets S and F of \widehat{G} , the *boundary* of F relative to S , denoted by $\partial_S(F)$, is defined by

$$\partial_S(F) = \{\alpha \in F \mid N_{\alpha,\gamma}^\beta > 0 \text{ for some } \gamma \in S, \beta \notin F\} \cup \{\alpha \notin F \mid N_{\alpha,\gamma}^\beta > 0 \text{ for some } \gamma \in S, \beta \in F\}.$$

The *weighted cardinality* $|F|_w$ of a finite subset F of \widehat{G} is given by

$$|F|_w = \sum_{\alpha \in F} d_\alpha^2.$$

D. Kyed proves a compact quantum group G is coamenable if and only if there exists a Følner sequence in \widehat{G} .

Theorem 2.3 (Følner condition for amenable discrete quantum groups [Kyed 2008, Corollary 4.10]). *A compact quantum group G is coamenable if and only if there exists a sequence $\{F_n\}_{n=1}^\infty$ (a right Følner sequence) of finite subsets of \widehat{G} such that*

$$\lim_{n \rightarrow \infty} \frac{|\partial_S(F_n)|_w}{|F_n|_w} = 0$$

for every finite nonempty subset S of \widehat{G} .

3. Mean ergodic theorem for amenable discrete quantum groups

In this section we prove the generalized mean ergodic theorem.

Theorem 3.1. *Let G be a coamenable compact quantum group with counit ε and $\{F_n\}_{n=1}^\infty$ be a right Følner sequence of \widehat{G} . For a representation $\pi : A = C(G) \rightarrow B(H)$, we have*

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \pi(\chi(\alpha)) = P \tag{3-1}$$

under the strong operator topology, where P is the orthogonal projection from H onto

$$H_{\text{inv}} = \{x \in H \mid \pi(a)x = \varepsilon(a)x \text{ for all } a \in A\}.$$

We divide the proof into two major steps:

Step 1. *We show that $H_{\text{inv}} = K$ for $K = \{x \in H \mid \pi(\chi(\alpha))x = d_\alpha x \text{ for all } \alpha \in \widehat{G}\}$.*

Step 2. *The sequence $\{(1/|F_n|_w) \sum_{\alpha \in F_n} d_\alpha \pi(\chi(\alpha))\}_{n=1}^\infty$ converges to the projection from H onto K .*

Proof of Step 1 for Theorem 3.1. We proceed via two lemmas:

Lemma 3.2. *If a state φ on $A = C(G)$ for a compact quantum group G satisfies that $\varphi(\chi(\alpha)) = d_\alpha$ for all $\alpha \in \widehat{G}$, then $\varphi = \varepsilon$.*

Proof. It suffices to show that $\varphi(u_{ij}^\alpha) = \delta_{ij}$ for every $\alpha \in \widehat{G}$ and an arbitrary unitary $U = (u_{ij}^\alpha)_{1 \leq i, j \leq d_\alpha} \in \alpha$.

Let $\varphi(U)$ be the matrix $(\varphi(u_{ij}^\alpha))$ in $M_{d_\alpha}(\mathbb{C})$. Note that φ is a state, hence completely positive. By a generalized Schwarz inequality of M. Choi [1974, Corollary 2.8], we have

$$\varphi(U)\varphi(U^*) \leq \varphi(UU^*) = 1.$$

Let Tr be the normalized trace of $M_{d_\alpha}(\mathbb{C})$. Since $\varphi(\chi(\alpha)) = d_\alpha$, we get $\text{Tr}(\varphi(U)) = 1$. It follows that

$$\begin{aligned} 0 &\leq \text{Tr}((\varphi(U) - 1)(\varphi(U) - 1)^*) \\ &= \text{Tr}(\varphi(U)\varphi(U)^* - \varphi(U)^* - \varphi(U) + 1) \\ &= \text{Tr}(\varphi(U)\varphi(U)^*) - 1 \\ &= \text{Tr}(\varphi(U)\varphi(U^*)) - 1 \\ &\leq \text{Tr}(\varphi(UU^*)) - 1 = 0. \end{aligned}$$

Hence, $\text{Tr}((\varphi(U) - 1)(\varphi(U) - 1)^*) = 0$, which implies that $\varphi(U) = 1$. This ends the proof. □

Lemma 3.3. *Let $\pi : A = C(G) \rightarrow B(H)$ be a representation. Then*

$$H_{\text{inv}} = K = \{x \in H \mid \pi(\chi(\alpha))x = d_\alpha x \text{ for all } \alpha \in \widehat{G}\}.$$

Proof. Note that $\varepsilon(\chi(\alpha)) = d_\alpha$ for all $\alpha \in \widehat{G}$ [Woronowicz 1998, Formula (5.11)]. Hence $H_{\text{inv}} \subseteq K$.

To show $K \subseteq H_{\text{inv}}$, we can assume $K \neq 0$ without loss of generality.

Let $x \in K$ be an arbitrarily chosen unit vector. By Lemma 3.2, the state φ_x defined by $\varphi_x(a) = \langle \pi(a)x, x \rangle$ for all $a \in A$ is ε , since $\varphi_x(\chi(\alpha)) = d_\alpha$ for all $\alpha \in \widehat{G}$.

For every $a \in A$, we have

$$\begin{aligned} \|\pi(a)x - \varepsilon(a)x\|^2 &= \langle \pi(a)x - \varepsilon(a)x, \pi(a)x - \varepsilon(a)x \rangle \\ &= \langle \pi(a)x, \pi(a)x \rangle - \langle \varepsilon(a)x, \pi(a)x \rangle - \langle \pi(a)x, \varepsilon(a)x \rangle + \langle \varepsilon(a)x, \varepsilon(a)x \rangle \\ &= \langle \pi(a^*a)x, x \rangle - \langle \varepsilon(a)\pi(a^*)x, x \rangle - \overline{\varepsilon(a)}\langle \pi(a)x, x \rangle + |\varepsilon(a)|^2 \\ &= \varepsilon(a^*a) - \varepsilon(a)\varepsilon(a^*) - |\varepsilon(a)|^2 + |\varepsilon(a)|^2 \\ &= 0. \end{aligned}$$

This proves that $K \subseteq H_{\text{inv}}$, and so concludes the proof of Step 1. \square

Proof of Step 2 for Theorem 3.1. We start with a lemma:

Lemma 3.4. *The orthogonal complement H_{inv}^\perp of H_{inv} is*

$$V := \overline{\text{Span}\{\pi(\chi(\alpha))x - d_\alpha x \mid \alpha \in \widehat{G}, x \in H\}}.$$

We need the following well-known fact in functional analysis:

Proposition 3.5. *Suppose $\{T_j\}_{j \in J}$ is a family of bounded operators on a Hilbert space H . Then the orthogonal complement of $\bigcap_{j \in J} \ker T_j$ is*

$$\overline{\text{ran}\{T_j^* \mid j \in J\}},$$

the closed linear span of the ranges $\text{ran } T_j^$ of T_j^* for all j in J .*

Proof of Lemma 3.4. Consider the family of operators $\{\pi(\chi(\alpha)) - d_\alpha\}_{\alpha \in \widehat{G}}$ in $B(H)$. These are self-adjoint operators, since

$$(\pi(\chi(\alpha)) - d_\alpha)^* = \pi(\chi(\bar{\alpha})) - d_{\bar{\alpha}},$$

Applying Proposition 3.5 to $\{\pi(\chi(\alpha)) - d_\alpha\}_{\alpha \in \widehat{G}}$ gives the proof. \square

Now we are ready to finish the proof of Theorem 3.1.

For every $x \in H_{\text{inv}}$ and all n , we have

$$\frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \pi(\chi(\alpha))x = \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha^2 x = x.$$

Next we show that

$$\frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \pi(\chi(\alpha))z \rightarrow 0$$

for all $z \in V$ as $n \rightarrow \infty$. By Lemma 3.4, we only need to prove it for z of the form $\pi(\chi(\gamma))y - d_\gamma y$ for every $y \in H$ and $\gamma \in \widehat{G}$.

For every $y \in H$ and $\gamma \in \widehat{G}$, we have

$$\begin{aligned}
 & \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \pi(\chi(\alpha)) (\pi(\chi(\gamma))y - d_\gamma y) \\
 &= \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \left(\sum_{\alpha \in F_n \setminus \partial_\gamma F_n} + \sum_{\alpha \in F_n \cap \partial_\gamma F_n} \right) d_\alpha \pi(\chi(\alpha) \chi(\gamma)) y - d_\alpha d_\gamma \pi(\chi(\alpha)) y \\
 & \hspace{15em} \text{(by Theorem 2.3 and since } \chi(\alpha) \chi(\gamma) = \chi(\alpha\gamma)) \\
 &= \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n \setminus \partial_\gamma F_n} d_\alpha \pi(\chi(\alpha\gamma)) y - d_\alpha d_\gamma \pi(\chi(\alpha)) y \quad (\alpha\gamma = \sum_{\beta \in F_n} N_{\alpha,\gamma}^\beta \beta \text{ when } \alpha \in F_n \setminus \partial_\gamma F_n) \\
 &= \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \left(\sum_{\alpha \in F_n \setminus \partial_\gamma F_n} \sum_{\beta \in F_n} d_\alpha N_{\alpha,\gamma}^\beta \pi(\chi(\beta)) y - \sum_{\alpha \in F_n \setminus \partial_\gamma F_n} d_\alpha d_\gamma \pi(\chi(\alpha)) y \right) \\
 & \hspace{15em} (N_{\alpha,\gamma}^\beta = N_{\beta,\bar{\gamma}}^\alpha \text{ and } d_\gamma = d_{\bar{\gamma}}) \\
 &= \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \left(\sum_{\alpha \in F_n \setminus \partial_\gamma F_n} \sum_{\beta \in F_n} d_\alpha N_{\beta,\bar{\gamma}}^\alpha \pi(\chi(\beta)) y - \sum_{\alpha \in F_n \setminus \partial_\gamma F_n} d_\alpha d_{\bar{\gamma}} \pi(\chi(\alpha)) y \right) \\
 &= \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \left(\sum_{\alpha \in F_n \setminus \partial_\gamma F_n} \sum_{\beta \in F_n} d_\alpha N_{\beta,\bar{\gamma}}^\alpha \pi(\chi(\beta)) y - \sum_{\alpha \in F_n \setminus \partial_\gamma F_n} \left[\sum_{\beta \in F_n} + \sum_{\beta \notin F_n} \right] N_{\alpha,\bar{\gamma}}^\beta d_\beta \pi(\chi(\alpha)) y \right) \\
 & \hspace{15em} \text{(exchange } \alpha \text{ and } \beta \text{ in the second term)} \\
 &= \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \left(\sum_{\alpha \in F_n \setminus \partial_\gamma F_n} \sum_{\beta \in F_n} d_\alpha N_{\beta,\bar{\gamma}}^\alpha \pi(\chi(\beta)) y - \sum_{\beta \in F_n \setminus \partial_\gamma F_n} \left[\sum_{\alpha \in F_n} + \sum_{\alpha \notin F_n} \right] N_{\beta,\bar{\gamma}}^\alpha d_\alpha \pi(\chi(\beta)) y \right) \\
 & \hspace{15em} \text{(common terms are canceled)} \\
 &= \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \left(\sum_{\alpha \in F_n \setminus \partial_\gamma F_n} \sum_{\beta \in F_n \cap \partial_\gamma F_n} d_\alpha N_{\beta,\bar{\gamma}}^\alpha \pi(\chi(\beta)) y \right. \\
 & \quad \left. - \sum_{\beta \in F_n \setminus \partial_\gamma F_n} \sum_{\alpha \in F_n \cap \partial_\gamma F_n} N_{\beta,\bar{\gamma}}^\alpha d_\beta \pi(\chi(\beta)) y - \sum_{\beta \in F_n \setminus \partial_\gamma F_n} \sum_{\alpha \notin F_n} N_{\beta,\bar{\gamma}}^\alpha d_\alpha \pi(\chi(\beta)) y \right) \\
 &= 0.
 \end{aligned}$$

Note that the last equality above holds since, by Theorem 2.3, we have the following:

$$\begin{aligned}
 (1) \quad & \frac{1}{|F_n|_w} \left\| \sum_{\alpha \in F_n \setminus \partial_\gamma F_n} \sum_{\beta \in F_n \cap \partial_\gamma F_n} d_\alpha N_{\beta,\bar{\gamma}}^\alpha \pi(\chi(\beta)) y \right\| \leq \frac{1}{|F_n|_w} \sum_{\beta \in F_n \cap \partial_\gamma F_n} \sum_{\alpha \in F_n} d_\alpha N_{\beta,\bar{\gamma}}^\alpha d_\beta \|y\| \\
 & \leq \frac{1}{|F_n|_w} \sum_{\beta \in F_n \cap \partial_\gamma F_n} d_\beta^2 d_{\bar{\gamma}} \|y\| \rightarrow 0; \\
 (2) \quad & \frac{1}{|F_n|_w} \left\| \sum_{\beta \in F_n \setminus \partial_\gamma F_n} \sum_{\alpha \in F_n \cap \partial_\gamma F_n} N_{\beta,\bar{\gamma}}^\alpha d_\alpha \pi(\chi(\beta)) y \right\| \leq \frac{1}{|F_n|_w} \sum_{\beta \in F_n \setminus \partial_\gamma F_n} \sum_{\alpha \in F_n \cap \partial_\gamma F_n} N_{\beta,\bar{\gamma}}^\alpha d_\alpha d_\beta \|y\| \\
 & = \frac{1}{|F_n|_w} \sum_{\beta \in F_n \setminus \partial_\gamma F_n} \sum_{\alpha \in F_n \cap \partial_\gamma F_n} N_{\alpha,\gamma}^\beta d_\alpha d_\beta \|y\| \\
 & \leq \frac{1}{|F_n|_w} \sum_{\alpha \in F_n \cap \partial_\gamma F_n} d_\alpha^2 d_\gamma \|y\| \rightarrow 0;
 \end{aligned}$$

$$\begin{aligned}
 (3) \quad \frac{1}{|F_n|_w} \left\| \sum_{\beta \in F_n \setminus \partial_\gamma F_n} \sum_{\alpha \notin F_n} N_{\beta, \bar{\gamma}}^\alpha d_\alpha \pi(\chi(\beta))y \right\| &\leq \frac{1}{|F_n|_w} \sum_{\beta \in F_n \setminus \partial_\gamma F_n} \sum_{\alpha \notin F_n} N_{\beta, \bar{\gamma}}^\alpha d_\alpha d_\beta \|y\| \\
 &= \frac{1}{|F_n|_w} \sum_{\beta \in F_n \setminus \partial_\gamma F_n} \sum_{\alpha \notin F_n, N_{\beta, \bar{\gamma}}^\alpha > 0} N_{\beta, \bar{\gamma}}^\alpha d_\alpha d_\beta \|y\| \\
 &\leq \frac{1}{|F_n|_w} \sum_{\beta \in \partial_{\bar{\gamma}} F_n} \sum_{\alpha \in \widehat{G}} N_{\beta, \bar{\gamma}}^\alpha d_\alpha d_\beta \|y\| \\
 &= \frac{1}{|F_n|_w} \sum_{\beta \in \partial_{\bar{\gamma}} F_n} d_\beta^2 d_{\bar{\gamma}} \|y\| \rightarrow 0 \quad \text{as } n \rightarrow \infty.
 \end{aligned}$$

This completes proof of Step 2 and therefore of Theorem 3.1. □

For a representation $\pi : B \rightarrow B(H)$ of a unital C^* -algebra B , define the *commutant* $\pi(B)'$ of $\pi(B)$ by

$$\pi(B)' = \{T \in B(H) \mid T\pi(b) = \pi(b)T \text{ for all } b \in B\}.$$

Corollary 3.6. *In the setting of Theorem 3.1, the projection P is in $\pi(A)' \cap \overline{\pi(A)}^{\text{SOT}}$.*

Proof. The left-hand side of (3-1) is in $\overline{\pi(A)}^{\text{SOT}}$; hence, so is P . Moreover, for all $x, y \in H$ and $a \in A$, we have

$$\langle \pi(a)Px, y \rangle = \varepsilon(a)\langle Px, y \rangle$$

and

$$\langle P\pi(a)x, y \rangle = \langle \pi(a)x, Py \rangle = \langle x, \pi(a^*)Py \rangle = \langle x, \varepsilon(a^*)Py \rangle = \varepsilon(a)\langle Px, y \rangle.$$

This proves $P \in \pi(A)'$. □

As a consequence, we have the following:

Corollary 3.7. *Assume that φ is a pure state on $A = C(G)$ for a coamenable compact quantum group G and $\{F_n\}_{n=1}^\infty$ is a right Følner sequence of \widehat{G} . Then*

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \varphi(\chi(\alpha)) = \begin{cases} 1 & \text{if } \varphi = \varepsilon, \\ 0 & \text{if } \varphi \neq \varepsilon. \end{cases}$$

Proof. When $\varphi = \varepsilon$, we have $\varepsilon(\chi(\alpha)) = d_\alpha$ for all $\alpha \in \widehat{G}$ [Woronowicz 1998, Formula (5.11)]. Hence,

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \varepsilon(\chi(\alpha)) = 1.$$

Suppose $\varphi \neq \varepsilon$.

Consider the GNS representation $\pi_\varphi : A \rightarrow B(L^2(A, \varphi))$. We have

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \varphi(\chi(\alpha)) = \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \langle \pi_\varphi(\chi(\alpha))(\hat{1}), \hat{1} \rangle = \langle P(\hat{1}), \hat{1} \rangle.$$

Hence, $\lim_{n \rightarrow \infty} (1/|F_n|_w) \sum_{\alpha \in F_n} d_\alpha \varphi(\chi(\alpha)) \neq 0$ if and only if $P(\hat{1}) \neq 0$.

To prove $\lim_{n \rightarrow \infty} (1/|F_n|_w) \sum_{\alpha \in F_n} d_\alpha \varphi(\chi(\alpha)) = 0$ for $\varphi \neq \varepsilon$, it suffices to prove $P(\hat{1}) = 0$.

Suppose $P(\hat{1}) \neq 0$. Then $H_{\text{inv}} \neq 0$. By Corollary 3.6, the space H_{inv} is an invariant subspace of $L^2(A, \varphi)$. Note that π_φ is irreducible since φ is a pure state. Hence $H_{\text{inv}} = L^2(A, \varphi)$. In particular, $\hat{1} \in H_{\text{inv}}$. Thus, for all $a \in A$, we have $\pi_\varphi(a)(\hat{1}) = \varepsilon(a)\hat{1}$. It follows that

$$\varphi(a) = \langle \pi_\varphi(a)(\hat{1}), \hat{1} \rangle = \langle \varepsilon(a)\hat{1}, \hat{1} \rangle = \varepsilon(a)$$

for all $a \in A$, which contradicts that $\varphi \neq \varepsilon$. □

4. A Wiener-type theorem for compact metrizable groups

In this section, we prove the following Wiener-type theorem:

Theorem 4.1. *Let G be a compact metrizable group. Given y in G and a right Følner sequence $\{F_n\}_{n=1}^\infty$ of \widehat{G} , for a finite Borel measure μ on G one has*

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \sum_{1 \leq i, j \leq d_\alpha} \mu(u_{ij}^\alpha \overline{u_{ij}^\alpha}(y)) = \mu\{y\} \quad \text{and} \quad \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \sum_{1 \leq i, j \leq d_\alpha} |\mu(u_{ij}^\alpha)|^2 = \sum_{x \in G} \mu\{x\}^2.$$

Hence, μ is continuous if and only if

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \sum_{1 \leq i, j \leq d_\alpha} |\mu(u_{ij}^\alpha)|^2 = 0.$$

Here $(u_{ij}^\alpha)_{1 \leq i, j \leq d_\alpha} \in M_{d_\alpha}(C(G))$ stands for a unitary matrix presenting $\alpha \in \widehat{G}$.

From now on G stands for a compact metrizable group. When thinking of G as a compact quantum group, the coproduct

$$\Delta : C(G) \rightarrow C(G) \otimes C(G)$$

is given by $\Delta(f)(x, y) = f(xy)$, the coinverse $\kappa : C(G) \rightarrow C(G)$ is given by $\kappa(f)(x) = f(x^{-1})$ and the counit $\varepsilon : C(G) \rightarrow \mathbb{C}$ is given by $\varepsilon(f) = f(e_G)$ for all $f \in C(G)$ and $x, y \in G$. Here, e_G is the neutral element of G .

Definition 4.2. Given a finite Borel measure μ on G , the *conjugate* $\bar{\mu}$ of μ is defined by

$$\bar{\mu}(f) = \int_G f(x^{-1}) d\mu(x) = \mu(\kappa(f))$$

for all $f \in C(G)$, and $\bar{\mu}$ is also a finite Borel measure on G . In other words, $\bar{\mu}(E) = \mu(E^{-1})$ for every Borel subset E of G .

For $x \in G$, use δ_x to denote the Dirac measure at x .

The *convolution* $\mu * \nu$ of two finite Borel measures μ and ν on G is defined by

$$\mu * \nu(f) = (\mu \otimes \nu)\Delta(f) = \int_G \int_G f(xy) d\mu(x) d\nu(y)$$

for all $f \in C(G)$. For every Borel subset E of G , we have

$$\mu * \nu(E) = \int_G \nu(x^{-1}E) d\mu(x) = \int_G \mu(Ey^{-1}) d\nu(y).$$

If either μ or ν is continuous, then so is $\mu * \nu$.

We can write a finite Borel measure μ on G as $\mu = \sum_i \lambda_i \delta_{x_i} + \mu_C$ for every atom x_i with $\mu\{x_i\} = \lambda_i$ and a finite continuous Borel measure μ_C .

Lemma 4.3. *Let μ be a finite Borel measure on G and $\{F_n\}_{n=1}^\infty$ be a right Følner sequence of \widehat{G} . Then*

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \mu(\chi(\alpha)) = \mu\{e_G\}.$$

Proof. By Corollary 3.7, the sequence $\{(1/|F_n|_w) \sum_{\alpha \in F_n} d_\alpha \chi(\alpha)(x)\} \subseteq C(G)$ converges pointwise to 1_{e_G} (the characteristic function of $\{e_G\}$). The terms of the sequence are bounded by 1 for all $x \in G$; hence, by Lebesgue's dominated convergence theorem [Rudin 1987, Theorem 1.34], we have

$$\begin{aligned} \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \mu(\chi(\alpha)) &= \lim_{n \rightarrow \infty} \int_G \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \chi(\alpha)(x) d\mu(x) \\ &= \int_G \lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \chi(\alpha)(x) d\mu(x) \\ &= \int_G 1_{e_G} d\mu = \mu\{e_G\}. \quad \square \end{aligned}$$

Proof of Theorem 4.1. Given a finite Borel measure μ on G and $y \in G$, consider the measure $\mu * \delta_{y^{-1}}$. By Lemma 4.3, we have

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \mu * \delta_{y^{-1}}(\chi(\alpha)) = \mu * \delta_{y^{-1}}\{e_G\}.$$

Note that

$$\begin{aligned} \mu * \delta_{y^{-1}}(\chi(\alpha)) &= \int_G \int_G \chi(\alpha)(xz) d\mu(x) d\delta_{y^{-1}}(z) \\ &= \int_G \chi(\alpha)(xy^{-1}) d\mu(x) \\ &= \int_G \sum_{1 \leq i \leq d_\alpha} u_{ii}^\alpha(xy^{-1}) d\mu(x) \\ &= \int_G \sum_{1 \leq i \leq d_\alpha} \sum_{1 \leq j \leq d_\alpha} u_{ij}^\alpha(x) u_{ji}^\alpha(y^{-1}) d\mu(x) \\ &= \int_G \sum_{1 \leq i \leq d_\alpha} \sum_{1 \leq j \leq d_\alpha} u_{ij}^\alpha(x) \overline{u_{ij}^\alpha(y)} d\mu(x). \end{aligned}$$

Moreover,

$$\mu * \delta_{y^{-1}}\{e_G\} = \int_G \int_G 1_{e_G}(xz) d\mu(x) d\delta_{y^{-1}}(z) = \int_G 1_{e_G}(xy^{-1}) d\mu(x) = \mu\{y\}.$$

This completes the proof of the first part.

Applying Lemma 4.3 to $\mu * \bar{\mu}$, we have

$$\lim_{n \rightarrow \infty} \frac{1}{|F_n|_w} \sum_{\alpha \in F_n} d_\alpha \mu * \bar{\mu}(\chi(\alpha)) = \mu * \bar{\mu}\{e_G\}.$$

Since $\mu = \sum_{x_i \text{ atoms}} \lambda_i \delta_{x_i} + \mu_C$ with $\lambda_i = \mu\{x_i\}$ and μ_C a finite continuous Borel measure, we have

$$\bar{\mu} = \sum_{x_i \text{ atoms}} \lambda_i \bar{\delta}_{x_i} + \bar{\mu}_C = \sum_{x_i \text{ atoms}} \lambda_i \delta_{x_i^{-1}} + \bar{\mu}_C.$$

Hence,

$$\mu * \bar{\mu} = \sum_i \sum_j \lambda_i \lambda_j \delta_{x_i} * \delta_{x_j^{-1}} + \sum_i \lambda_i \delta_{x_i} * \bar{\mu}_C + \sum_j \lambda_j \mu_C * \delta_{x_j^{-1}} + \mu_C * \bar{\mu}_C.$$

Note that $\sum_i \lambda_i \delta_{x_i} * \bar{\mu}_C + \sum_j \lambda_j \mu_C * \delta_{x_j^{-1}} + \mu_C * \bar{\mu}_C$ is a finite continuous measure and

$$\sum_{i,j} \lambda_i \lambda_j \delta_{x_i} * \delta_{x_j^{-1}} = \sum_{i,j} \lambda_i \lambda_j \delta_{x_i x_j^{-1}}.$$

It follows that

$$\mu * \bar{\mu}\{e_G\} = \sum_{x_i \text{ atoms}} \lambda_i^2 = \sum_{x_i \text{ atoms}} \mu\{x_i\}^2 = \sum_{x \in G} \mu\{x\}^2.$$

On the other hand,

$$\begin{aligned} \mu * \bar{\mu}(\chi(\alpha)) &= \int_G \int_G \chi(\alpha)(xy) d\mu(x) d\bar{\mu}(y) \\ &= \int_G \int_G \chi(\alpha)(xy^{-1}) d\mu(x) d\mu(y) \\ &= \int_G \int_G \sum_{1 \leq i \leq d_\alpha} u_{ii}^\alpha(xy^{-1}) d\mu(x) d\mu(y) \\ &= \int_G \int_G \sum_{1 \leq i \leq d_\alpha} \sum_{1 \leq j \leq d_\alpha} u_{ij}^\alpha(x) u_{ji}^\alpha(y^{-1}) d\mu(x) d\mu(y) \\ &= \sum_{1 \leq i \leq d_\alpha} \sum_{1 \leq j \leq d_\alpha} \int_G u_{ij}^\alpha(x) d\mu(x) \int_G \overline{u_{ij}^\alpha(y)} d\mu(y) \\ &= \sum_{1 \leq i, j \leq d_\alpha} |\mu(u_{ij}^\alpha)|^2. \end{aligned}$$

This ends the proof of the first part, and the second follows immediately. □

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