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Crossed products of Cuntz algebras by quasi-free actions of abelian groups

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1 Introduction

The crossed products of $C^*$-algebras give us plenty of interesting examples and the structures of them have been examined by several authors. In [KK1] and [KK2], A. Kishimoto and A. Kumjian dealt with, among others, the crossed products of Cuntz algebras by quasi-free actions of the real group $\mathbb{R}$. In [Ka1] and [Ka2], we examined the crossed products of Cuntz algebras by quasi-free actions of arbitrary locally compact, second countable, abelian groups. In this note, we summarize the results of [Ka1] and [Ka2], and discuss several examples.

2 Preliminaries

In this section, we review some basic objects and fix the notation.

For $n = 2, 3, \ldots$, the Cuntz algebra $O_n$ is the universal $C^*$-algebra generated by $n$ isometries $S_1, S_2, \ldots, S_n$, satisfying $\sum_{i=1}^{n} S_i S_i^* = 1$ [C1]. In this note, we only consider the case $n < \infty$. For similar results on the crossed products of $O_\infty$, see [Ka3]. For $k \in \mathbb{N} = \{0, 1, \ldots\}$, we define the set $W_n^{(k)}$ of $k$-tuples by $W_n^{(0)} = \{\emptyset\}$ and

$$W_n^{(k)} = \{(i_1, i_2, \ldots, i_k) \mid i_j \in \{1, 2, \ldots, n\}\}.$$ 

We set $W_n = \bigcup_{k=0}^{\infty} W_n^{(k)}$. For $\mu = (i_1, i_2, \ldots, i_k) \in W_n$, we denote its length $k$ by $|\mu|$, and set $S_\mu = S_{i_1} S_{i_2} \cdots S_{i_k} \in O_n$. Note that $|\emptyset| = 0$, $S_\emptyset = 1$. For $\mu = (i_1, i_2, \ldots, i_k), \nu = (j_1, j_2, \ldots, j_l) \in W_n$, we define their product $\mu \nu \in W_n$ by $\mu \nu = (i_1, i_2, \ldots, i_k, j_1, j_2, \ldots, j_l)$.

Let $G$ be a locally compact abelian group which satisfies the second axiom of countability and $\Gamma$ be the dual group of $G$. We always use $+$ for multiplicative operations of abelian groups except for $\mathbb{T}$, which is the group of the unit circle in the complex plane $\mathbb{C}$. The pairing of $t \in G$ and $\gamma \in \Gamma$ is denoted by $\langle t | \gamma \rangle \in \mathbb{T}$.

Let us take $\omega = (\omega_1, \omega_2, \ldots, \omega_n) \in \Gamma^n$ and fix it. Since the $n$ isometries $\langle t | \omega_1 \rangle S_1, \langle t | \omega_2 \rangle S_2, \ldots, \langle t | \omega_n \rangle S_n$ also satisfy the relation above for any $t \in G$, there is a $*$-automorphism $\alpha_{t}^\omega : O_n \to O_n$ such that $\alpha_{t}^\omega(S_i) = \langle t | \omega_i \rangle S_i$ for $i = 1, 2, \ldots, n$. One can see that $\alpha_{t}^\omega : G \ni t \mapsto \alpha_{t}^\omega \in \text{Aut}(O_n)$ is a strongly continuous group homomorphism.
Definition 2.1 Let $\omega = (\omega_1, \omega_2, \ldots, \omega_n) \in \Gamma^n$ be given. We define the action $\alpha^\omega : G \curvearrowright \mathcal{O}_n$ by

$$\alpha^\omega_t(S_i) = \left( t | \omega_i \right) S_i \quad (i = 1, 2, \ldots, n, \ t \in G).$$

The action $\alpha^\omega : G \curvearrowright \mathcal{O}_n$ becomes quasi-free (for a definition of quasi-free actions on Cuntz algebras, see [E]). Conversely, any quasi-free action of the abelian group $G$ on $\mathcal{O}_n$ is conjugate to $\alpha^\omega$ for some $\omega \in \Gamma^n$.

Since the abelian group $G$ is amenable, the reduced crossed product of the action $\alpha^\omega : G \curvearrowright \mathcal{O}_n$ coincides with the full crossed product of it. We denote it by $\mathcal{O}_n \rtimes_{\alpha^\omega} G$ and call it the crossed product. The crossed product $\mathcal{O}_n \rtimes_{\alpha^\omega} G$ has a $C^*$-subalgebra $C_1 \times_{\alpha^\omega} G$ which is isomorphic to $C_0(\Gamma)$. Throughout this paper, we always consider $C_0(\Gamma)$ as a $C^*$-subalgebra of $\mathcal{O}_n \rtimes_{\alpha^\omega} G$, and use $f, g, \ldots$ for denoting elements of $C_0(\Gamma) \subset \mathcal{O}_n \rtimes_{\alpha^\omega} G$. The Cuntz algebra $\mathcal{O}_n$ is naturally embedded into the multiplier algebra $M(\mathcal{O}_n \rtimes_{\alpha^\omega} G)$ of $\mathcal{O}_n \rtimes_{\alpha^\omega} G$. For any $\mu = (i_1, i_2, \ldots, i_k)$ in $\mathcal{W}_n$, we define an element $\omega_\mu$ of $\Gamma$ by $\omega_\mu = \sum_{j=1}^{k} \omega_{i_j}$. For $\gamma_0 \in \Gamma$, we define a (reverse) shift automorphism $\sigma_{\gamma_0} : C_0(\Gamma) \to C_0(\Gamma)$ by $(\sigma_{\gamma_0} f)(\gamma) = f(\gamma + \gamma_0)$ for $f \in C_0(\Gamma)$. Once noting that $\alpha^\omega_t(S_\mu) = \left( t | \omega_\mu \right) S_\mu$ for $\mu \in \mathcal{W}_n$, one can easily verify that $fS_\mu = S_\mu \sigma_{\omega_\mu} f$ for any $f \in C_0(\Gamma) \subset \mathcal{O}_n \rtimes_{\alpha^\omega} G$ and any $\mu \in \mathcal{W}_n$. From this fact, we have $\mathcal{O}_n \rtimes_{\alpha^\omega} G = \text{span}\{S_\mu f S_\nu^* \mid \mu, \nu \in \mathcal{W}_n, \ f \in C_0(\Gamma)\}$, where $\text{span}$ means the closure of the linear span.

3 The ideal structure of $\mathcal{O}_n \rtimes_{\alpha^\omega} G$

In [Ka1], we completely determined the ideal structures of the crossed product $\mathcal{O}_n \rtimes_{\alpha^\omega} G$. For an ideal $I$ of the crossed product $\mathcal{O}_n \rtimes_{\alpha^\omega} G$, we define the closed subset $X_I$ of $\Gamma$ by $I \cap C_0(\Gamma) = C_0(\Gamma \setminus X_I)$. The closed subset $X_I$ satisfies

(i) For any $\gamma \in X_I$ and any $i \in \{1, 2, \ldots, n\}$, we have $\gamma + \omega_i \in X_I$.

(ii) For any $\gamma \in X_I$, there exists $i \in \{1, 2, \ldots, n\}$ such that $\gamma - \omega_i \in X_I$.

The closed subset of $\Gamma$ satisfying two conditions above is said to be $\omega$-invariant. A closed set $X$ is $\omega$-invariant if and only if $X = \bigcup_{i=1}^{n} (X + \omega_i)$. For a closed $\omega$-invariant subset $X$ of $\Gamma$, we define $I_X \subset \mathcal{O}_n \rtimes_{\alpha^\omega} G$ by

$$I_X = \text{span}\{S_\mu f S_\nu^* \mid \mu, \nu \in \mathcal{W}_n, \ f \in C_0(\Gamma \setminus X)\}.$$ One can see that $I_X$ is an ideal of $\mathcal{O}_n \rtimes_{\alpha^\omega} G$ and invariant under the gauge action $\beta$ of $\Gamma$ on $\mathcal{O}_n \rtimes_{\alpha^\omega} G$, which is defined by $\beta_t(S_\mu f S_\nu^*) = t^{[\nu] - [\mu]} S_\mu f S_\nu^*$ for $\mu, \nu \in \mathcal{W}_n$, $f \in C_0(\Gamma)$ and $t \in \Gamma$. With a technique using conditional expectations, we can prove the following.

Proposition 3.1 ([Ka1, Theorem 3.14]) The two maps $I \mapsto X_I$ and $X \mapsto I$ between the set of gauge invariant ideals of $\mathcal{O}_n \rtimes_{\alpha^\omega} G$ and the set of closed $\omega$-invariant subsets of $\Gamma$ are the inverses of each other.

The ideal structure of $\mathcal{O}_n \rtimes_{\alpha^\omega} G$ depends on whether $\omega \in \Gamma^n$ satisfies the following condition:
Condition 3.2 For each $i \in \{1, 2, \ldots, n\}$, one of the following two conditions is satisfied:

(i) For any positive integer $k$, $k\omega_i \neq 0$.

(ii) There exists $j \neq i$ such that $-\omega_j$ is in the closed semigroup generated by $\omega_1, \omega_2, \ldots, \omega_n$ and $-\omega_i$.

This condition is an analogue of Condition (II) in the case of Cuntz-Krieger algebras [C2] or Condition (K) in the case of graph algebras [KPRR].

Theorem 3.3 ([Ka1, Theorem 5.2]) When $\omega$ satisfies Condition 3.2, any ideal is gauge invariant. Hence there is a one-to-one correspondence between the set of ideals of $O_n \rtimes_{\alpha^\omega} G$ and the set of closed $\omega$-invariant subsets of $\Gamma$.

When $\omega$ does not satisfy Condition 3.2, there exists $i_0 \in \{1, 2, \ldots, n\}$ such that $k\omega_{i_0} = 0$ for some positive integer $k$, and that $-\omega_i$ is not in the closed semigroup generated by $\omega_1, \omega_2, \ldots, \omega_n$ and $-\omega_{i_0}$ for any $i \neq i_0$. Note that such $i_0$ is unique. Let $\Gamma'$ be the quotient group of $\Gamma$ by the subgroup generated by $\omega_1$ and denote by $[\gamma]$ the image of $\gamma \in \Gamma$. Define a $C^*$-subalgebra $A$ of $O_n \rtimes_{\alpha^\omega} G$ by $A = \overline{\text{span}}\{S_{i_0}^{k}fS_{i_0}^{-l} | f \in C_0(\Gamma), k, l \in \mathbb{N}\}$. The $C^*$-algebra $A$ is isomorphic to the Toeplitz algebra of the Hilbert module coming from the automorphism $\sigma_{\omega_{i_0}}$ of $C_0(\Gamma)$, hence there is a surjective map $\pi : A \to C_0(\Gamma) \rtimes_{\sigma_{\omega_{i_0}}} \mathbb{Z}$. It is not hard to see that there is a one-to-one correspondence between the set of ideals of $C_0(\Gamma) \rtimes_{\sigma_{\omega_{i_0}}} \mathbb{Z}$ and the set of closed subset of $\Gamma' \times \mathbb{T}$. For an ideal $I$ of $O_n \rtimes_{\alpha^\omega} G$, we define the closed subset $Y_I$ of $\Gamma' \times \mathbb{T}$ which corresponds to the ideal $\pi(I \cap A)$. The closed set $Y_I$ satisfies that $([\gamma + \omega_i], \theta') \in Y_I$ for any $i \neq i_0$ any $\theta' \in \mathbb{T}$ and any $([\gamma], \theta) \in Y_I$. Conversely, for any closed set $Y$ of $\Gamma' \times \mathbb{T}$ satisfying the condition above, we can construct the ideal $I_Y$ of $O_n \rtimes_{\alpha^\omega} G$ so that $Y_{I_Y} = Y$ (see Definition 5.17 and Proposition 5.23 of [Ka1]).

Theorem 3.4 ([Ka1, Theorem 5.49]) In the above setting, we have $I_{Y_I} = I$ for any ideal $I$ of $O_n \rtimes_{\alpha^\omega} G$. Thus there is a one-to-one correspondence between the set of ideals of $O_n \rtimes_{\alpha^\omega} G$ and the set of closed subsets of $\Gamma' \times \mathbb{T}$ satisfying the condition above.

On the way to prove the two theorems above, we get another proofs of the following known facts (see [Ki] and [OP]):

- $O_n \rtimes_{\alpha^\omega} G$ is simple if and only if the closed semigroup generated by $\omega_1, \omega_2, \ldots, \omega_n$ and $-\omega_i$ is equal to $\Gamma$ for any $i = 1, 2, \ldots, n$ [Ka1, Theorem 4.8].

- $O_n \rtimes_{\alpha^\omega} G$ is primitive if and only if the closed group generated by $\omega_1, \omega_2, \ldots, \omega_n$ is equal to $\Gamma$ [Ka1, Theorem 4.12].

By Theorem 3.3 and Theorem 3.4, we can show that the strong Connes spectrum $\tilde{\Gamma}(\alpha^\omega)$ of the action $\alpha^\omega$ is the intersection of the closed semigroups generated by $\omega_1, \omega_2, \ldots, \omega_n$ and $-\omega_i$ where $i = 1, 2, \ldots, n$ [Ka1, Proposition 6.2]. The crossed product $O_n \rtimes_{\alpha^\omega} G$ is
isomorphic to the Cuntz Pimsner algebra of a certain Hilbert bimodule. From this fact, we have the following exact sequence.

\[
\begin{array}{c}
K_0(C_0(\Gamma)) \xrightarrow{id-\sum_{i=1}^n(\sigma_{\omega_i})_*} K_0(C_0(\Gamma)) \xrightarrow{i_*} K_0(\mathcal{O}_n \rtimes_{\alpha^\omega} G) \\
\uparrow \downarrow \downarrow \\
K_1(\mathcal{O}_n \rtimes_{\alpha^\omega} G) \xleftarrow{i_*} K_1(C_0(\Gamma)) \xleftarrow{id-\sum_{i=1}^n(\sigma_{\omega_i})_*} K_1(C_0(\Gamma))
\end{array}
\]

where \( i \) is the embedding \( i : C_0(\Gamma) \hookrightarrow \mathcal{O}_n \rtimes_{\alpha^\omega} G \) [Ka1, Proposition 6.5].

4 AF-embeddability and pure infiniteness of \( \mathcal{O}_n \rtimes_{\alpha^\omega} G \)

In [Ka2], we gave a sufficient condition for the crossed products \( \mathcal{O}_n \rtimes_{\alpha^\omega} G \) to be AF-embeddable. To the best of the author's knowledge, this is the first case to have succeeded in embedding crossed products of purely infinite C*-algebras into AF-algebras except trivial cases.

**Theorem 4.1** ([Ka2, Theorem 3.8]) If \( -\omega_i \notin \{\omega_\mu \mid \mu \in \mathcal{W}_n\} \) for any \( i = 1, 2, \ldots, n \), then the crossed product \( \mathcal{O}_n \rtimes_{\alpha^\omega} G \) is AF-embeddable.

In [KK1], Kishimoto and Kumjian proved that \( \mathcal{O}_n \rtimes_{\alpha^\omega} \mathbb{R} \) becomes stable and projectionless when \( \omega \in \mathbb{R}^n \) satisfies \( -\omega_i \notin \{\omega_\mu \mid \mu \in \mathcal{W}_n\} \). Hence \( \mathcal{O}_n \rtimes_{\alpha^\omega} \mathbb{R} \) is stably finite in this case. Theorem 4.1 gives another proof of this fact.

In [KK2], they gave a necessary and sufficient condition that \( \mathcal{O}_n \rtimes_{\alpha^\omega} \mathbb{R} \) becomes simple and purely infinite. Here, we generalize their result.

**Theorem 4.2** ([Ka2, Corollary 4.9]) The crossed product \( \mathcal{O}_n \rtimes_{\alpha^\omega} G \) is simple and purely infinite if and only if \( \Gamma = \{\omega_\mu \mid \mu \in \mathcal{W}_n\} \).

By the two theorems above and the characterization of simplicity, we have the following dichotomy.

**Corollary 4.3** ([Ka2, Corollary 4.8]) The crossed product \( \mathcal{O}_n \rtimes_{\alpha^\omega} G \) is either purely infinite or AF-embeddable when it is simple.

5 Examples

5.1 When \( G \) is compact

When \( G \) is compact, its dual group \( \Gamma \) becomes discrete. In this case, for any \( \omega \in \Gamma^\omega \) the crossed product \( \mathcal{O}_n \rtimes_{\alpha^\omega} G \) is a graph algebra of some skew product graph which is row-finite (see [KP]) and a part of our results here has been already proved in, for example, [BPRS]. Particularly, we have the following.

**Proposition 5.1** ([Ka2, Proposition 3.9]) When \( G \) is compact, the following are equiv-
(i) $-\omega_i \notin \{\omega_\mu \mid \mu \in \mathcal{W}_n\}$ for any $i = 1, 2, \ldots, n$.
(ii) The crossed product $\mathcal{O}_n \times_{\alpha^\omega} G$ is stably finite.
(iii) The crossed product $\mathcal{O}_n \times_{\alpha^\omega} G$ is $\text{AF}$-embeddable.
(iv) The crossed product $\mathcal{O}_n \times_{\alpha^\omega} G$ itself is an $\text{AF}$-algebra.

5.2 When $G$ is discrete

When $G$ is discrete, its dual group $\Gamma$ becomes compact. Let us denote by $\Lambda_\omega$ a closed semigroup generated by $\omega_1, \omega_2, \ldots, \omega_n$. One can see that $-\omega_i \in \Lambda_\omega$ for $i = 1, 2, \ldots, n$. Hence any $\omega \in \Gamma^n$ satisfies Condition 3.2. Since the closed set $X$ is $\omega$-invariant if and only if $X + \Lambda_\omega = X$, the set of all closed $\omega$-invariant subsets of $\Gamma$ is one-to-one correspondent to the set of all closed subset of $\Gamma/\Lambda_\omega$. Here note that $\Lambda_\omega$ is a closed subgroup of $\Gamma$. By Theorem 3.3, the set of all ideals of $\mathcal{O}_n \times_{\alpha^\omega} G$ corresponds bijectively to the set of all closed subset of $\Gamma/\Lambda_\omega$.

We can examine the ideal structures of $\mathcal{O}_n \times_{\alpha^\omega} G$ directly as well as other structures of it. Let $G'$ be the quotient of $G$ by the closed subgroup

$$\{t \in G \mid \alpha_t^\omega = \text{id}\} = \{t \in G \mid \langle t, \omega_i \rangle = 1 \text{ for } i = 1, 2, \ldots, n\} = \{t \in G \mid \langle t, \gamma \rangle = 1 \text{ for any } \gamma \in \Lambda_\omega\}. $$

The dual group of $G'$ is naturally isomorphic to $\Lambda_\omega$. Since $\omega \in \Lambda_\omega^n \subset \Gamma^n$, we can define an action $\alpha^\omega : G'' \actson \mathcal{O}_n$. The crossed product $\mathcal{O}_n \times_{\alpha^\omega} G''$ is simple and purely infinite by Theorem 4.2. The crossed product $\mathcal{O}_n \times_{\alpha^\omega} G$ becomes a continuous field over the compact space $\Gamma/\Lambda_\omega$ whose fiber of any point is isomorphic to $\mathcal{O}_n \times_{\alpha^\omega} G'$. From this observation, we can easily see that the set of all ideals of $\mathcal{O}_n \times_{\alpha^\omega} G$ corresponds bijectively to the set of all closed subset of $\Gamma/\Lambda_\omega$.

When $G$ is discrete, the crossed product $\mathcal{O}_n \times_{\alpha^\omega} G$ has an infinite projection, hence is never $\text{AF}$-embeddable.

5.3 When $G = \mathbb{R}^m$

When $G = \mathbb{R}^m$, its dual group $\Gamma$ is also $\mathbb{R}^m$. For $\omega \in (\mathbb{R}^m)^n$, we define the following.

**Definition 5.2** Let $\omega = (\omega_1, \omega_2, \ldots, \omega_n) \in (\mathbb{R}^m)^n$. We denote the affine space generated by $\omega_1, \omega_2, \ldots, \omega_n \in \mathbb{R}^m$ and their convex hull by

$$L_\omega = \left\{ \sum_{i=1}^n t_i \omega_i \in \mathbb{R}^m \left| \sum_{i=1}^n t_i = 1 \right. \right\}, \quad C_\omega = \left\{ \sum_{i=1}^n t_i \omega_i \in \mathbb{R}^m \left| t_i \geq 0, \sum_{i=1}^n t_i = 1 \right. \right\},$$

respectively. The set $C_\omega$ is a closed subset of $L_\omega$. We denote by $O_\omega$ the interior of $C_\omega$ in $L_\omega$.

We define the three types for elements of $(\mathbb{R}^m)^n$.

**Definition 5.3** Let $\omega = (\omega_1, \omega_2, \ldots, \omega_n) \in (\mathbb{R}^m)^n$. The element $\omega$ is said to be of type $(\ast)$ if $0 \notin C_\omega$, to be of type $(0)$ if $0 \in C_\omega \setminus O_\omega$, and to be of type $(\ast)$ if $0 \in O_\omega$. 


On this type, we can prove the following. We omit proofs.

**Lemma 5.4** If $\omega$ is of type $(+)$, then there exists $v \in \mathbb{R}^m \setminus \{0\}$ such that the inner product $\omega_i \cdot v$ of $\omega_i$ and $v$ is non-negative for any $i = 1, 2, \ldots, n$. Moreover when $m \geq 2$, we can find such $v$ so that there exists $i_0$ with $\omega_i \cdot v = 0$.

**Lemma 5.5** If $\omega$ is of type $(0)$, then there exists $v \in \mathbb{R}^m \setminus \{0\}$ such that $\omega_i \cdot v \geq 0$ for any $i = 1, 2, \ldots, n$, and there exists $i_0$ with $\omega_i \cdot v = 0$.

From these two lemmas, we get the following characterizations of type $(−)$ and type $(+)$. 

**Proposition 5.6** An element $\omega$ is of type $(−)$ if and only if the closed semigroup generated by $\omega_1, \omega_2, \ldots, \omega_n$ is a group. An element $\omega$ is of type $(+)$ if and only if $-\omega_i \notin \{\omega_{\mu} : \mu \in \mathcal{W}_n\}$ for any $i = 1, 2, \ldots, n$.

Combining this proposition with Theorem 4.1 and Theorem 4.2, we have the following. An element $\omega$ is called aperiodic if the closed group generated by $\omega_1, \omega_2, \ldots, \omega_n$ is $\mathbb{R}^m$.

**Proposition 5.7** The crossed product $O_n \rtimes_{\omega^\omega} \mathbb{R}^m$ is AF-embeddable if $\omega$ is of type $(+)$. The crossed product $O_n \rtimes_{\omega^\omega} \mathbb{R}^m$ is simple and purely infinite if and only if $\omega$ is of type $(−)$ and aperiodic.

It is easy to see that an element $\omega$ does not satisfy Condition 3.2 if and only if 0 is an extreme point of $C_\omega$ and there is only one $i \in \{1, 2, \ldots, n\}$ with $\omega_i = 0$. In this case, $\omega$ is of type (0). The following is a consequence of Lemma 5.4 and Lemma 5.5.

**Proposition 5.8** If $\omega$ is of type (0) or if $\omega$ is of type $(+)$ and $m \geq 2$, then there exists $i_0 \in \{1, 2, \ldots, n\}$ such that the closed semigroup generated by $\omega_1, \omega_2, \ldots, \omega_n$ and $-\omega_0$ is not $\mathbb{R}^m$. Hence in this case, the crossed product $O_n \rtimes_{\omega^\omega} \mathbb{R}^m$ is not simple.

The condition for simplicity follows from the proposition above.

**Proposition 5.9** When $m = 1$, the crossed product $O_n \rtimes_{\omega^\omega} \mathbb{R}^m$ is simple if and only if $\omega$ is of type $(+) or (−)$ and aperiodic.

When $m \geq 2$, the crossed product $O_n \rtimes_{\omega^\omega} \mathbb{R}^m$ is simple if and only if $\omega$ is of type $(−)$ and aperiodic.

When $m \geq 2$, the crossed product $O_n \rtimes_{\omega^\omega} \mathbb{R}^m$ is purely infinite if it is simple.
References


