Quantum Dynamical Systems
with Quasi–Discrete Spectrum

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Quantum Dynamical Systems

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Abstract. We study totally ergodic quantum dynamical systems with quasi–discrete spectrum. We investigate the classification problem for such systems in terms of algebraic invariants. The results are noncommutative analogs of the theory of Abramov.

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I. Introduction

Let \((X, \mu), \mu(X) = 1,\) be a standard Lebesgue space and let \(\alpha : X \to X\) be an automorphism of \((X, \mu)\). Then \(\alpha\) defines an unitary operator, called the Koopman operator \([K]\), in \(L^2(X, d\mu)\) and denoted by the same letter.

In the important papers [VN] and [HvN], von Neumann and Halmos classified all classical ergodic systems for which the Koopman operator has purely discrete spectrum. The main result of their analysis is that such systems are classified by the spectrum, which forms a discrete subgroup of \(U(1)\), and each such a system is conjugate to a shift on a compact abelian group, the Pontriagin dual of the spectrum. Here, and throughout the paper, \(U(1)\) is the group of complex numbers with absolute value 1 and discrete topology. For a clear account of that result, see e.g. [CFS], [W], or [Si].

This theory was extended to noncommutative setting by Olsen, Pedersen and Takesaki [OPT]. It turns out that noncommutative ergodic systems with discrete spectrum are classified by the spectrum of the automorphism, which as above is a discrete subgroup \(H\) of \(U(1)\) and a second cohomology class of \(H\). This theorem is stated more carefully in Section II.

The notions of quasi-eigenvalue and quasi-eigenfunction were introduced by von Neumann and Halmos [H]. They proved, using those concepts, that there exist spectrally equivalent but not conjugate automorphisms with mixed spectrum. Later Abramov [Ab] gave a complete classification of totally ergodic systems with quasi-discrete spectrum. A topological version of Abramov’s theory for minimal systems was discussed in [HaP], [HoP].

Let us shortly describe what quasi-eigenvalues and quasi-eigenfunctions are and state the Abramov’s theorem. With the above notation \(\alpha\) is called totally ergodic if \(\alpha^n\) is ergodic for every \(n = 1, 2, \ldots\). Ordinary eigenvectors and eigenvalues of \(\alpha\) are called, correspondingly, quasi-eigenvectors and quasi-eigenvalues of the first order. A function \(f \in L^2(X, d\mu)\) is called a quasi-eigenvector of the second order if

\[\alpha(f) = \phi f,\]

where \(\phi\) is an eigenvector of \(\alpha\). In such a case \(\phi\) is called a quasi-eigenvalue of the second order. Continuing this process one obtains quasi-eigenvectors and quasi-eigenvalues of arbitrary order - see Section II for a more precise definition. The crucial observation is that, if \(\alpha\) is totally ergodic, quasi-eigenvectors corresponding to different quasi-eigenvalues are orthogonal. One considers then the situation when \(L^2(X, d\mu)\) has a basis consisting of quasi-eigenvectors of \(\alpha\). If this is the case we say that \(\alpha\) has purely quasi-discrete spectrum. The Abramov’s theorem can be formulated as follows.
Theorem I.1. [Ab] There is a one-to-one correspondence between the conjugacy classes of totally ergodic dynamical systems with purely quasi-discrete spectrum and the equivalence classes of pairs $(H, R)$ where $H$ is a discrete abelian group of the form $H = \bigcup_{n=1}^{\infty} H_n$ where $H_1 \subset H_2 \subset \ldots$ is an increasing sequence of discrete abelian groups, $H_1 \subset U(1)$ and $H_1$ has no non-trivial elements of finite order, and $R$ is a homomorphism of $H$ such that for every $n = 1, 2, \ldots$ the kernel of $R^n$ is the group $H_n$.

The goal of this paper is to extend the Abramov theorem to the quantum mechanical case i.e. when the space $X$ is replaced by a noncommutative von Neumann algebra. Our proofs and organization of the material follow closely that of Abramov's with several important differences. Among them are:

- The set of quasi-eigenvalues forms a group but not with respect to operator multiplication but rather a twisted version of it denoted by $\ast$ in this paper.
- We introduce a natural concept of a normalized basis of quasi-eigenvectors which simplifies proofs of the Equivalence Theorem and the Representation Theorem.

The paper is organized as follows. In Section II we introduce a fairly general setup and precisely formulate the problem. We become more restrictive in Section III and in particular we assume that already the second order quasi-eigenvectors form a basis in the corresponding $L^2$-space. This is likely a minor conceptual simplification which makes for a much more readable presentation of the material. We show in that section how to construct group-theoretic invariants for totally ergodic quantum dynamical systems with purely quasi-discrete spectrum (of the second order). We prove the equivalence theorem in Section IV, and the representation theorem in Section V. Finally, Section VI contains a simple example of such a quantum dynamical system.

II. Quantum Ergodic Systems

We begin by reviewing the basic concepts which are used throughout the paper. We will work within the von Neumann algebra framework, see e.g. [BR], as this is the natural setup for noncommutative (quantum) ergodic theory. We will adopt the following definition of a quantum dynamical system.

Definition II.1. A quantum dynamical system is a quadruple $(\mathfrak{A}, G, \alpha, \tau)$ with the following properties:

(i) $\mathfrak{A}$ is a von Neumann algebra with a separable dual.
(ii) $G$ is a locally compact abelian group. Physically relevant are the groups $G = \mathbb{Z}$ (in which case the system is called a quantum map) and $G = \mathbb{R}$ (in which case the system is called a quantum flow);
(iii) $\alpha : G \to \text{Aut} (\mathfrak{A})$ is an action of $G$ on $\mathfrak{A}$ by von Neumann algebra automorphisms;
(iv) $\tau$ is a $G$-invariant, normal, faithful state on $\mathfrak{A}$.

Let us comment on some of the assumptions. Since locally compact abelian groups are amenable, it allows one to define the time average of an observable and prove ergodic theorems, see e.g. [L], [J], and references therein. Also, the separability assumption is motivated by physics: Hilbert spaces of states of physical systems are always separable. However, using the Zorn lemma one can attempt to eliminate it in our constructions.

We will denote $\mathcal{K} = L^2(\mathfrak{A}, \tau)$, the GNS representation space of $\mathfrak{A}$ associated to the state $\tau$. Since $\mathfrak{A}$ has a separable dual, $\mathcal{K}$ is a separable Hilbert space. It is natural to think of $\mathcal{K}$ as a quantum version of the classical Koopman space. The automorphisms $\alpha_g$ extend to unitary operators of the $\mathcal{K}$-spaces. By a slight abuse of notation, we continue to denote them by $\alpha_g$.

**Definition II.2.** Two quantum dynamical systems $(\mathfrak{A}, G, \alpha, \tau)$ and $(\mathfrak{B}, G, \beta, \omega)$ are conjugate if there exists an isomorphism of von Neumann algebras $\Phi : \mathfrak{A} \to \mathfrak{B}$ such that

(i) $\Phi \circ \alpha = \beta \circ \Phi$;

(ii) $\omega \circ \Phi = \tau$.

An non-zero element $U \in \mathcal{K}$ is an eigenvector of $\alpha$ if $\alpha_g(U) = \lambda(g)U$, where $\lambda(g) \in U(1)$. Clearly, each $g \to \lambda(g)$ is a character of the group $G$. The set $\text{Spec}_p(\alpha)$ of all such characters is called the point spectrum of $\alpha$.

**Definition II.3.** A quantum dynamical system $(\mathfrak{A}, G, \alpha, \tau)$ is called a system with purely discrete spectrum if $\mathcal{K}$ has an orthonormal basis consisting of eigenvectors of $\alpha$.

As a consequence of the separability assumption, $\text{Spec}_p(\alpha)$ is a countable subset of the dual group $\hat{G}$.

Ergodic theory of von Neumann algebras has been studied by many authors. For references and a variety of results, see e.g. [C], [KL1,2], [KLMR], [L] and [J]. For our purposes, the following definition of quantum ergodicity will be sufficient.

**Definition II.4.** A quantum dynamical system $(\mathfrak{A}, G, \alpha, \tau)$ is called ergodic if the only $G$-invariant elements of $\mathcal{K}$ are scalar multiples of $I$.

Equivalently, the eigenspace of $\alpha_g$ corresponding to the eigenvalue 1 is one dimensional and consists of the scalar multiples of the identity operator. For quantum ergodic systems, the time and ensemble averages of an observable are equal. Also one has the following classification theorem due to Olsen, Pedersen and Takesaki [OPT].
Theorem II.5. [OPT] There is a one-to-one correspondence between the conjugacy classes of ergodic quantum dynamical systems with purely discrete spectrum and the family of pairs \((H, \sigma)\) where \(H \subset \hat{G}\) is a discrete group and \(\sigma\) is a second cohomology class of \(H\).

In fact, in analogy with the commutative theory, every quantum dynamical system is conjugate to a shift on the noncommutative deformation of \(\hat{H}\) determined by \(\sigma\).

Definition II.6. A quantum dynamical system \((\mathcal{A}, G, \alpha, \tau)\) is called totally ergodic if for every \(g \in G\) the only elements of \(\mathcal{K}\) invariant under \(\alpha_g\), are scalar multiples of \(I\).

We shall call the eigenvectors of \(\alpha\) quasi-eigenvectors of the first order. Similarly, eigenvalues of \(\alpha\) are called quasi-eigenvalues of the first order. The set of normalized quasi-eigenvectors of the first order is denoted by \(G_1\) while the set of all quasi-eigenvalues of the first order is denoted by \(H_1\). We define the set \(G_n\) of normalized quasi-eigenvectors of \(n\)-th order and the set \(H_n\) of quasi-eigenvalues of \(n\)-th order inductively. Suppose that \(G_n\) and \(H_n\) are defined.

Definition II.7. An non-zero element \(U \in \mathcal{K}\) is a quasi-eigenvector of order \(n + 1\) of \(\alpha\) if \(\alpha_g(U) = \lambda(g)U\), where \(\lambda(g) \in \mathcal{A} \cap G_n\). Then \(\lambda\) is called a quasi-eigenvalue of order \(n + 1\).

Definition II.8. A quantum dynamical system \((\mathcal{A}, G, \alpha, \tau)\) is called a system with purely quasi-discrete spectrum if \(\mathcal{K}\) has an orthonormal basis consisting of quasi-eigenvectors of \(\alpha\).

The subject of this paper is the classification problem for (noncommutative) totally ergodic systems with quasi-discrete spectrum. This is to be solved by constructing a complete set of algebraic invariants of such systems. Unfortunately the classification problem in such a generality seems to lead to an excessively complicated system of algebraic invariants. In what follows we present a detailed account of the classification theory under several additional assumptions which are satisfied in the original example that has motivated our work on the subject.
III. Classification of Quasi-Discrete Systems

To simplify the exposition of the results we are going to make the following assumptions:

1. We consider only $G = \mathbb{Z}$, i.e. quantum maps. The automorphism $\alpha_1$ corresponding to the generator $1$ of $\mathbb{Z}$ will simply be denoted by $\alpha$.

2. We assume that $\mathcal{K}$ has an orthonormal basis consisting of the second order quasi-eigenvectors of $\alpha$.

3. We require that $\tau$ is a normalized trace.

Additionally, throughout the rest of the paper we assume that the system $(\mathfrak{A}, \mathbb{Z}, \alpha, \tau)$ is ergodic. We do explicitly mention when total ergodicity is used.

With extra effort the classification program can be presumably carried out for arbitrary abelian locally compact groups and arbitrary quasi-discrete spectrum. The trace assumption is used in the proof of unitarity in the following proposition and possibly is not really needed. In any case it seems likely that ergodicity and discreteness of the quasi-spectrum will force any invariant state to be a trace.

Every constant is an eigenvector belonging to the eigenvalue $\lambda = 1$, and therefore $H_1 \subset G_1$. Moreover, obviously:

$$H_1 \subset H_2 \subset G_1 \subset G_2.$$  \hspace{1cm} (1)

**Proposition III.1.** Let $\lambda$ be an eigenvalue of $\alpha$. If $U_\lambda \in \mathcal{K}$ is a normalized second order quasi-eigenvector of $\alpha$:

$$\alpha(U_\lambda) = \lambda U_\lambda,$$  \hspace{1cm} (2)

then $U_\lambda \in \mathfrak{A}$ and $U_\lambda$ is unitary.

**Proof.** This needs a little von Neumann algebras theory from [Ar]. Let $P^\delta \subset L^2 (\mathfrak{A}, \tau)$ be the closure of $\Delta^{1/4} \mathfrak{A}_+ 1$, where $\Delta$ is the modular operator, $\mathfrak{A}_+$ is the positive part of $\mathfrak{A}$ and where $1 \in \mathfrak{A} \subset L^2 (\mathfrak{A}, \tau)$ is the unit in $\mathfrak{A}$. It follows from this definition that $P^\delta$ is invariant under $\alpha$. It is known that every $x \in L^2 (\mathfrak{A}, \tau)$ has a unique decomposition:

$$x = u |x|,$$

where $u \in \mathfrak{A}$ is a partial isometry and $|x| \in P^\delta$. Write $U_\lambda = u |U_\lambda|$ in (2). Then:

$$\alpha(u)\alpha(|U_\lambda|) = (\lambda u) |U_\lambda|$$

It follows that $|U_\lambda|$ is an invariant vector for $\alpha$ and so, by ergodicity, it is equal to $1$. But that means that $U_\lambda \in \mathfrak{A}$. Applying the ergodicity assumption to $U_\lambda^* U_\lambda$ we see that $U_\lambda^* U_\lambda = 1$.

Since $1 - U_\lambda U_\lambda^*$ is positive and $\tau (1 - U_\lambda U_\lambda^*) = \tau (1 - U_\lambda^* U_\lambda) = 0$ we see that $U_\lambda$ is unitary. \(\square\)
Proposition III.2. If $U, V \in G_2$ belong to the same quasi-eigenvalue $\lambda$ then there is a constant $C$, $|C| = 1$, such that $U = CV$.

Proof. Applying $\alpha$ to $U^{-1}V$ yields:

$$\alpha(U^{-1}V) = U^{-1} \lambda^{-1} \lambda V = U^{-1}V.$$  

It follows from ergodicity of $\alpha$ that $U^{-1}V$ is a constant. \(\Box\)

Let us recall from [OPT] the following structural result about $G_1$.

Proposition III.3. For each pair $\lambda, \mu \in H_1$, we have

$$U_\lambda U_\mu = \sigma(\lambda, \mu) U_\mu U_\lambda, \tag{3}$$

where $U_\lambda, U_\mu \in G_1$ are the corresponding eigenvectors and $\sigma : H_1 \times H_1 \to U(1)$. Furthermore, $\sigma$ has the following properties:

$$\sigma(\lambda, \lambda) = 1, \tag{4}$$

$$\sigma(\lambda, \mu \nu) = \sigma(\lambda, \mu) \sigma(\lambda, \nu), \tag{5}$$

and

$$\sigma(\mu, \lambda) = \sigma(\lambda, \mu)^{-1}. \tag{6}$$

A map $\sigma : H_1 \times H_1 \to U(1)$ satisfying (4), (5), (6) is called a symplectic bicharacter.

The following lemma deals with effects of noncommutativity of $\mathfrak{A}$ on the classification problem.

Lemma III.4.

(i) If $U_\lambda \in G_2$ belongs to quasi-eigenvalue $\lambda \in H_2$ then there exist a number $\phi(\lambda) \in U(1)$ such that

$$U_\lambda^{-1} \lambda U_\lambda = \phi(\lambda) \lambda.$$  

(ii) If $U \in G_2$ and $V \in G_1$ then $UVU^{-1} \in G_1$.

Proof. We verify by direct calculation that $U_\lambda^{-1} \lambda U_\lambda$ and $\lambda$ belong to the same eigenvalue of $\alpha$. Consequently, Proposition III.2 implies item (i).

If $U \in G_2$ belongs to $\lambda \in H_2$, $\lambda \in H_2 \subset G_1$ belongs to $R(\lambda) \in H_1$, and $V \in G_1$ belongs to $\mu \in H_1$, then we compute:

$$\alpha(UVU^{-1}) = \lambda U \mu \nu U^{-1} \lambda^{-1} = \mu \phi(\lambda) \lambda U \lambda^{-1} \lambda^{-1} U^{-1}$$

$$= \mu U \lambda \nu \lambda^{-1} U^{-1} = \mu \sigma(R(\lambda), \mu) UVU^{-1} \tag{7}$$

which proves (ii). In the above calculation we used (i) twice as well as Proposition III.3. \(\Box\)

If $\lambda, \mu \in H_2$ and $U_\lambda \in G_2$ is a quasi-eigenvector belonging to $\lambda$ we define the following product on $H_2$:

$$\lambda \ast \mu := \lambda U_\lambda \mu U_\lambda^{-1}. \tag{8}$$
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**Proposition III.5.** Each of the sets $H_1, G_1, G_2$ is a group under operator multiplication while $H_2$ is a group under $*$ multiplication. Moreover $H_1 \subset H_2$ is a subgroup.

**Proof.** The fact that $H_1$ and $G_1$ are groups follows from [OPT] so we need to concentrate on $H_2$ and $G_2$. We first verify that the right hand side of (8) is in $G_1$:

$$
\alpha(\lambda U_{\mu} U_{\lambda}^{-1}) = R(\lambda) R(\mu) \sigma(R(\lambda), R(\mu)) \cdot \lambda U_{\mu} U_{\lambda}^{-1}
$$

by (7). Here $R(\lambda)$ and $R(\mu)$ are eigenvalues corresponding to eigenvectors $\lambda$ and $\mu$. Additionally:

$$
\alpha(U_{\mu} U_{\lambda}) = \lambda U_{\lambda} U_{\mu} = \lambda U_{\lambda} U_{\lambda}^{-1} \cdot U_{\lambda} U_{\mu} = \lambda \cdot \mu \cdot U_{\lambda} U_{\mu}
$$

so that $\lambda \cdot \mu \in H_2$. Consequently the $*$- product is well defined. The identity operator $I \in \mathfrak{A}$ is the unit for this multiplication. Since

$$
\alpha(U_{\lambda}^{-1}) = \frac{\lambda^{-1}}{\phi(\lambda)} \cdot U_{\lambda}^{-1}
$$

the $*$ inverse of $\lambda$ is

$$
I(\lambda) := \frac{\lambda^{-1}}{\phi(\lambda)}
$$

with $\lambda^{-1}$ the operator multiplication inverse. Associativity of the $*$ multiplication follows from (9) which also shows that $G_2$ is a group under operator multiplication. Finally if $\lambda, \mu \in H_1$ then $\lambda \cdot \mu = \lambda \mu$. $\square$

We define a map $R : G_2 \rightarrow H_2$ by $R(U) := \lambda$ if $\alpha(U) = \lambda U$. In other words, $R$ assigns to a quasi-eigenvector the corresponding quasi-eigenvalue. Clearly $R$ maps $G_1 \subset G_2$ into $H_1 \subset H_2$. Also $R$ maps $H_2 \subset G_1$ into $H_1$.

**Proposition III.6.** The mapping $R : H_2 \rightarrow H_1$ has the following properties:

(i) For every $\lambda \in H_2$ and $\mu \in H_1$ we have $\mu \sigma(\mu, R(\lambda)) \in H_1$ and

$$
\lambda \cdot \mu \cdot I(\lambda) = \mu \sigma(\mu, R(\lambda), \mu).
$$

In particular, $H_1$ is a normal subgroup of $H_2$.

(ii) $R$ is a “twisted” homomorphism:

$$
R(\lambda \cdot \mu) = R(\lambda) \cdot \lambda \cdot R(\mu) \cdot I(\lambda) = R(\lambda) R(\mu) \sigma(R(\lambda), R(\mu)).
$$

(iii) The kernel of $R$ is the group $H_1$.

**Proof.** Item (i) is just a rephrasing of (7) and item (ii) follows directly from (9). Item (iii) is a consequence of ergodicity of $\alpha$, as eigenvectors corresponding to eigenvalue $\lambda = 1$ are proportional to the identity. $\square$
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Let \( N := \text{Image of } R \subset H_1 \). Equip \( N \) with the following product:

\[ n_1 * n_2 := n_1 n_2 \sigma(n_1, n_2) \in N, \]

where the last inclusion follows from Proposition III.6, item (i). It is easy to see that \( N \) is a group with respect to this product and \( R : H_2 \rightarrow R \) is a homomorphism. Consequently, we have the following short exact sequence of groups:

\[ 1 \longrightarrow H_1 \longrightarrow H_2 \xrightarrow{R} N \longrightarrow 1. \tag{13} \]

This sequence is an extension with abelian kernel, and the \( N \)-module structure on \( H_1 \) is given by (11), see [B].

**Proposition III.7.** The group \( H_2 \) is at most countable, and, assuming that \( \alpha \) is totally ergodic, \( H_1 \) has no nontrivial elements of finite order.

**Proof.** Since \( \alpha \) is assumed to be totally ergodic no nontrivial elements of finite order in \( H_1 \) can exist. Also \( H_1 \) is at most countable as a consequence of separability of \( \mathcal{K} \). Since \( R \) defines a one-to-one map \( H_2/H_1 \rightarrow H_1 \), the group \( H_2 \) is at most countable. \( \square \)

If \( U \) belongs to \( \lambda \in H_2 \) then \( \alpha(U) \) belongs to \( R(\lambda) * \lambda \). Thus it makes sense to study the properties of the map:

\[ k(\lambda) := R(\lambda) * \lambda. \tag{14} \]

**Proposition III.8.** The map \( k \) defined by (14) is an isomorphism of \( H_2 \). Moreover \( k(\lambda) * I(\lambda) \in H_1 \) and \( k(\lambda) = \lambda \) iff \( \lambda \in H_1 \).

**Proof.** \( k \) is a homomorphism since

\[ k(\lambda * \mu) = R(\lambda * \mu) * \lambda * \mu = R(\lambda) * \lambda * R(\mu) * I(\lambda) * \lambda * \mu = R(\lambda) * \lambda * R(\mu) * \mu = k(\lambda) * k(\mu) \]

by Proposition III.6. The inverse of \( k \) is \( k^{-1}(\lambda) = R(\lambda)^{-1} * \lambda \). Next \( k(\lambda) * I(\lambda) = R(\lambda) \) so it is in \( H_1 \). Finally \( k(\lambda) = \lambda \) iff \( R(\lambda) = 1 \) so \( \lambda \in H_1 \). \( \square \)

**Proposition III.9.** If the automorphism \( \alpha \) is totally ergodic, then quasi-eigenvectors belonging to different quasi-eigenvalues are orthogonal in \( \mathcal{K} \).

**Proof.** The statement is true for ordinary eigenvectors. Let \( \mathcal{K}_1 \) be the closed subspace of \( \mathcal{K} \) spanned by \( G_1 \), and let \( \mathcal{K}_2 \) be its orthogonal complement. The assumption of total ergodicity of \( \alpha \) is used in the following lemma which says that quasi-eigenvector which is not an eigenvector can not be a linear combination of eigenvectors.
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Lemma III.10. Suppose $U \in G_2$ is not in $G_1$ and belongs to $\lambda \in H_2$. Then $U \not\in K_1$.

Proof. Assume that

$$U = \sum_{\mu \in H_1} a_{\mu} U_{\mu}. \quad (15)$$

We can compute $\alpha^n(U)$ in two different ways. First use (15) and apply $\alpha^n$ to each $U_{\mu}$. This yields:

$$\alpha^n(U) = \sum_{\mu \in H_1} a'_{\mu} U_{\mu},$$

where $a'_{\mu}$ differs from $a_{\mu}$ by a phase. Secondly, use $\alpha(U) = \lambda U$ n-times and then expand:

$$\alpha^n(U) = \sum_{\mu \in H_1} a''_{\mu} U_{R(\lambda)^n \mu},$$

where, as before, $a''_{\mu}$ differs from $a_{\mu}$ by a phase. By Proposition III.7 $R(\lambda)^n \mu$ are all different. Consequently, for any $\mu$ there is an infinite number of coefficients in (15) equal, up to a phase, to $a_{\mu}$, and so they must be zero. □

Returning to the proof of Proposition III.9, if $U \in G_2$ and not in $G_1$, then we claim that $U$ is in $K_2$. In fact, let $U = U_1 + U_2$ be the orthogonal decomposition of $U$ with respect to $K = K_1 \oplus K_2$. It follows from Lemma III.10 that $U_2 \neq 0$. Since $\alpha$ is unitary, $\alpha(U_1) \in K_1$ and $\alpha(U_2) \in K_2$. Moreover $\lambda U_1 \in K_1$ because $G_1$ forms a group. For the same reason $\lambda U_2 \in K_2$ as:

$$(\mu, \lambda U_2) = (\lambda^{-1} \mu, U_2) = 0,$$

for $\mu \in G_1$. Consequently we have $\alpha(U_1) = \lambda U_1$ and $\alpha(U_2) = \lambda U_2$ which implies, in view of Proposition III.2, that $U_1 = C U_2$. This can happen only if $C = 0$ as $U_1$ and $U_2$ belong to perpendicular subspaces of $K$.

It remains to prove that if $U, V \in G_2$ are not in $G_1$ and belong to different quasi-eigenvalues $\lambda, \mu \in H_2$ then $U, V$ are orthogonal. But this is the same as proving that $U^{-1}V$ is orthogonal to $1 \in K_1$. Since $G_2$ is a group with respect to operator multiplication, $U^{-1}V \in G_2$ and belongs to quasi-eigenvalue $I(\lambda) \ast \mu$. If $U^{-1}V$ is not in $G_1$ then the orthogonality follows from the previous argument. It remains to consider the case when $U^{-1}V \in G_1$. But two elements of $G_1$ are orthogonal unless they belong to the same eigenvalue, and, since $\lambda \neq \mu$, $I(\lambda) \ast \mu \neq 1$. □

Corollary III.11. For every $\lambda \in H_2$ we have:

$$\tau(U_\lambda) = \begin{cases} 1 & \text{if } \lambda = 1 \\ 0 & \text{otherwise.} \end{cases}$$

Proof. This is a direct consequence of Proposition III.9 and $\tau(U_\lambda) = (1, U_\lambda)$. □
IV. Equivalence Theorem

In this section we spell out the complete set of group theoretic invariants for totally ergodic quantum dynamical systems with quasi-discrete spectrum of the second order. The equivalence theorem proved here says that if two such systems have the same set of invariants then they are conjugate.

If $H$ is a group, then a function $r : H \times H \to U(1)$ is called a 2-cocycle if

$$r(\lambda, \mu)r(\lambda\mu, \nu) = r(\lambda, \mu\nu)r(\mu, \nu),$$

(16)

for all $\lambda, \mu, \nu \in H$. A 2-cocycle $r$ is called trivial if there is a function $d : H \to U(1)$, such that $r(\lambda, \mu) = d(\lambda\mu)/d(\lambda)d(\mu)$. The set of equivalence classes of 2-cocycles mod trivial 2-cocycles is the second cohomology group $H^2(H)$ of group $H$ (with values in $U(1)$).

**Lemma IV.1.** Let $(\mathcal{A}, \mathbb{Z}, \alpha, \tau)$ be a totally ergodic quantum dynamical system with purely quasi-discrete spectrum of the second order. Choose an orthonormal basis $\{U_\lambda\}$, $\lambda \in H_2$, in $\mathcal{K}$, consisting of quasi-eigenvalues of $\alpha$ and such that $U_1 = 1$. Then for each pair $\lambda, \mu \in H_2$,

$$U_\lambda U_\mu = r(\lambda, \mu)U_{\lambda\mu},$$

(17)

where $r(\lambda, \mu)$ is a 2-cocycle on $H_2$. Moreover, any other orthonormal basis of $\mathcal{K}$ consisting of quasi-eigenvectors of $\alpha$ leads to a cohomologous $r$ and $\mathcal{A}$ is linearly spanned by $\{U_\lambda\}$.

**Proof.** (17) is a consequence of Proposition III.2, (10). The associativity of the operator multiplication implies that $r$ is a cocycle. If $\{V_\lambda\}$ is any other orthonormal basis of $\mathcal{K}$ consisting of quasi-eigenvectors of $\alpha$ then $V_\lambda = d(\lambda)U_\lambda$, $d(\lambda) \in U(1)$, and $d(\lambda)$ gives the equivalence of the corresponding cocycles. Finally, since $U_\lambda$ is a basis in $\mathcal{K}$ it follows that $\mathcal{A}$ is a $\sigma$-weakly closure of the linear span of $\{U_\lambda\}$. □

Since $H_2 \subset G_1$, given a choice of a basis in $\mathcal{K}$ we can write for any $\lambda \in H_2$:

$$\lambda = C(\lambda)U_{R(\lambda)},$$

(18)

where $C(\lambda) \in U(1)$. The main properties of the coefficients $C(\lambda)$ are summarized in the following lemma.

**Lemma IV.2.** With the above notation we have:

$$C(\lambda \ast \mu) = C(\lambda)C(\mu)r(\lambda, R(\mu))r(R(\lambda), \lambda \ast R(\mu) \ast I(\lambda))/r(\lambda \ast R(\mu) \ast I(\lambda), \lambda).$$

(19)

Additionally, if $\lambda \in H_1$ then $C(\lambda) = \lambda$.

**Proof.** Proof is a straightforward calculation using (17), (18), and Proposition III.6 which we omit. □

Let $D(\lambda)$ be the following $U(1)$-valued function on $H_2$:

$$D(\lambda) = \begin{cases} \lambda & \text{if } \lambda \in H_1 \\ 1 & \text{otherwise}. \end{cases}$$

(20)

We shall show below that one can choose a basis $\{U_\lambda\}$, $\lambda \in H_2$, in $\mathcal{K}$, consisting of quasi-eigenvalues of $\alpha$, such that the matrix elements of $\alpha$ are particularly simple.
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Proposition IV.3. There is a basis \( \{ U_\lambda \} \), \( \lambda \in H_2 \), in \( \mathcal{K} \), consisting of quasi-eigenvalues of \( \alpha \), such that
\[
\alpha(U_\lambda) = D(\lambda)U_{k(\lambda)}.
\] (21)
Such a basis will be called a normalized basis.

Proof. Notice that (21) says that \( \alpha(U_\lambda) = \lambda U_\lambda \) is \( \lambda \in H_1 \), which is always true, and \( \alpha(U_\lambda) = U_{k(\lambda)} \) if \( \lambda \not\in H_1 \). Consider the orbits of \( k \). If \( \lambda \in H_1 \) then \( k(\lambda) = \lambda \) and \( H_1 \) is the set of fixed points for \( k \). If \( \lambda \not\in H_1 \) then \( k^n(\lambda) = R(\lambda)^n = \lambda \) and, as \( H_1 \) has no elements of finite order, all \( k^n(\lambda) \) are different for different \( n \in \mathbb{Z} \). Choose one element \( s(\lambda) \) from each orbit \( k^n(\lambda) \), so that each \( \lambda \) can be uniquely written as \( \lambda = k^n(s(\lambda)) \). Choose \( U_s(\lambda) \) arbitrarily and set
\[
U_\lambda := \alpha^n (U_s(\lambda)).
\]
Since \( U_{k(\lambda)} = \alpha^{n+1} (U_s(\lambda)) \), (21) is clearly satisfied. \( \square \)

Let \( \{ U_\lambda \} \) be a normalized basis and let \( r(\lambda, \mu) \) be the corresponding 2-cocycle on \( H_2 \). Applying \( \alpha \) to (17) we infer that
\[
\frac{r(k(\lambda), k(\mu))}{r(\lambda, \mu)} = \frac{D(\lambda * \mu)}{D(\lambda)D(\mu)}.
\] (22)
Such a cocycle will be called a normalized cocycle. If \( V_\lambda = d(\lambda)U_\lambda \), \( d(\lambda) \in U(1) \) is another normalized basis then
\[
d(k(\lambda)) = d(\lambda).
\] (23)
By \( H^2_k(H_2) \) we denote the set of equivalence classes of normalized 2-cocycles on \( H_2 \) modulo \( k \)-invariant coboundaries (23).

Remark. If \( H_2 \) is abelian the set \( H^2_k(H_2) \) can be alternatively described as follows. Let \( \tilde{D} \) be a homomorphism of \( H_2 \) into \( U(1) \) extending the natural embedding \( H_1 \subset U(1) \). Such an extension is always possible for abelian groups [Ab]. Then, just like in Proposition (20), a basis \( \tilde{U}_\lambda \) can be constructed satisfying \( \alpha(\tilde{U}_\lambda) = \tilde{D}(\lambda)\tilde{U}_{k(\lambda)} \). The corresponding 2-cocycle \( \tilde{r} \) on \( H_2 \) is then \( k \)-invariant by an analog of (22), and cohomologous to \( r \) by Lemma IV.1. So, in this case, \( H^2_k(H_2) \) is the second group of \( k \)-invariant cohomologies of \( H_2 \). In general, when \( H_2 \) is not necessarily abelian, it is desirable to have a better description of \( H^2_k(H_2) \).

Let us denote by \([r]\) the cohomology class of \( r \) in \( H^2_k(H_2) \). When restricted to \( H_1 \) the conditions (22) and (23) are void. Moreover, since \( H_1 \) is abelian, there is a one-to-one correspondence between the second cohomology classes \([r]\) and symplectic bicharacters \( \sigma \), see Proposition III.3. The correspondence is given by:
\[
r(\lambda, \mu) = \sigma(\lambda, \mu) r(\mu, \lambda),
\] (24)
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see [OPT].

So far to a totally ergodic system with purely quasi-discrete spectrum of the second order we have associated the following algebraic structure:

1. A countable abelian group \( H_1 \subset U(1) \) which has no nontrivial elements of finite order.
2. A countable group \( H_2 \), such that \( H_1 \subset H_2 \) is a normal subgroup.
3. An isomorphism \( k : H_2 \leftrightarrow H_2 \) such that \( k(\lambda) \ast \lambda^{-1} \in H_1 \) and \( k(\lambda) = \lambda \) iff \( \lambda \in H_1 \).
4. A cohomology class \([r]\) in \( H^2_k(H_2)\).

**Definition IV.4.** A quadruple \((H_1, H_2, [r], k)\) satisfying conditions 1-4 above is called a quantum quasi-spectrum.

**Definition IV.5.** Two quantum quasi-spectra \((H_1, H_2, [r], k)\) and \((H'_1, H'_2, [r'], k')\) are called isomorphic if

1. \( H_1 = H'_1 \).
2. There exists an isomorphism \( \phi \) of the groups \( H_2 \) and \( H'_2 \) leaving fixed all the elements of the group \( H_1 = H'_1 \) and such that

\[
k = \phi^{-1}k'\phi, \quad [r] = \phi^*[r'],
\]

where \( \phi^* \) is the induced isomorphism of the cohomology groups.

We are now prepared to prove the following theorem which is the main result of the section.

**Theorem IV.6. (Equivalence Theorem)** Let \((\mathcal{A}, \mathbb{Z}, \alpha, \tau)\) and \((\mathcal{B}, \mathbb{Z}, \beta, \omega)\) be two totally ergodic quantum dynamical systems with purely quasi-discrete spectrum of the second order, and let \((H_1(\alpha), H_2(\alpha), [r_\alpha], k_\alpha)\) and \((H_1(\beta), H_2(\beta), [r_\beta], k_\beta)\) denote the corresponding quantum quasi-spectra. The following statements are equivalent:

1. The quantum quasi-spectra \((H_1(\alpha), H_2(\alpha), [r_\alpha], k_\alpha)\) and \((H_1(\beta), H_2(\beta), [r_\beta], k_\beta)\) are isomorphic;
2. \((\mathcal{A}, \mathbb{Z}, \alpha, \tau)\) and \((\mathcal{B}, \mathbb{Z}, \beta, \omega)\) are conjugate.

**Proof.** Only \((i) \rightarrow (ii)\) is non trivial. Let \(\mathcal{K}(\alpha)\) and \(\mathcal{K}(\beta)\) be the corresponding GNS Hilbert spaces. We are going to construct a conjugation \(\Phi : \mathcal{A} \rightarrow \mathcal{B}\) as an isomorphism implemented by a unitary map \(Q : \mathcal{K}(\alpha) \rightarrow \mathcal{K}(\beta)\). Let \(\{U_\lambda\}\) and \(\{V_\mu\}\) be normalized orthonormal basis in \(\mathcal{K}(\alpha)\) and \(\mathcal{K}(\beta)\) correspondingly, consisting of quasi-eigenvectors. Set:

\[
Q(U_\lambda) := V_{\phi(\lambda)}, \quad (25)
\]
where \( \phi \) is an isomorphism of \( H_2(\alpha) \) and \( H_2(\beta) \). By Lemma IV.1 we have \( U_\lambda U_\mu = r_\alpha(\lambda_1, \lambda_2) U_{\lambda_1 \ast \lambda_2} \) and \( V_\mu V_\nu = r_\beta(\mu_1, \mu_2) V_{\mu_1 \ast \mu_2} \). Since \( r_\alpha \) and \( \phi \circ r_\beta \) are cohomologous, we may assume, renormalizing \( V_\mu \) if necessary, that

\[
   r_\alpha(\lambda_1, \lambda_2) = r_\beta(\phi(\lambda_1), \phi(\lambda_2)).
\]

(26)

We can deduce from (26) that \( \Phi(U_\lambda) := QU_\lambda Q^{-1} = V_{\phi(\lambda)} \) as follows:

\[
   QU_\lambda Q^{-1} V_{\phi(\lambda_2)} = QU_\lambda U_\lambda = r_\alpha(\lambda_1, \lambda_2) QU_{\lambda_1 \ast \lambda_2} = r_\alpha(\lambda_1, \lambda_2) V_{\phi(\lambda_1 \ast \lambda_2)} = r_\beta(\phi(\lambda_1), \phi(\lambda_2)) V_{\phi(\lambda_1 \ast \phi(\lambda_2)} = V_{\phi(\lambda_1)} V_{\phi(\lambda_2)}
\]

But \( \mathfrak{A} \) and \( \mathfrak{B} \) are linearly generated by, correspondingly, \( U_\lambda \) and \( V_\mu \) and so \( \Phi \) extends to an isomorphism of \( \mathfrak{A} \) and \( \mathfrak{B} \). A straightforward calculation verifies that \( \Phi \circ \alpha = \beta \circ \Phi \):

\[
   (\Phi \circ \alpha) U_\lambda = D(\lambda) \Phi(U_{k_\lambda(\lambda)}) = D(\lambda) V_{\phi(k_\lambda(\lambda))} = D(\lambda) V_{k_\beta(\phi(\lambda))} = \beta V_{\phi(\lambda)} = (\beta \circ \Phi) U_\lambda
\]

Also \( \omega(\Phi(U_\lambda)) = \tau(U_\lambda) \) by Corollary III.11. It follows that \((\mathfrak{A}, \mathbb{Z}, \alpha, \tau)\) and \((\mathfrak{B}, \mathbb{Z}, \beta, \omega)\) are conjugate. \( \square \)

V. Representation Theorem

In this section we prove a representation theorem which says that for any system of invariants (i.e. a quantum quasi-spectrum) there is a corresponding quantum dynamical system with exactly that system of invariants. Consequently, the correspondence between the conjugacy classes of totally ergodic systems with purely quasi-discrete spectrum and the isomorphism classes of quantum quasi-spectra is onto.

**Theorem V.1. (Representation Theorem)** Let \((H_1, H_2, [r], k)\) be a quantum quasi-spectrum. There exists a totally ergodic quantum dynamical system \((\mathfrak{A}, \mathbb{Z}, \alpha, \tau)\) with purely quasi-discrete spectrum such that its quantum quasi-spectrum is isomorphic to \((H_1, H_2, [r], k)\)

**Proof.** Consider \( \mathcal{K} := l^2(H_2) \) and let \( \{\phi_\lambda\} \) be the canonical basis in \( \mathcal{K} \). Define \( \mathfrak{A} \) to be the von Neumann algebra generated by the following operators \( U_\lambda \):

\[
   U_\lambda \phi_\mu := r(\lambda, \mu) \phi_{\lambda \ast \mu},
\]

(27)

where \( r(\lambda, \mu) \) is a normalized 2-cocycle on \( H_2 \) corresponding to \([r]\). For any \( f \in \mathcal{K} \) we obtain

\[
   U_\lambda f(\mu) = r(\lambda, I(\lambda) \ast \mu)f(I(\lambda) \ast \mu).
\]
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It follows that

\[ U_\lambda U_\mu = r(\lambda, \mu) U_{\lambda^* \mu}, \]

Then set

\[ \beta \phi \lambda := D(\lambda) \phi_{k(\lambda)}, \] (28)

where \( D(\lambda) \in U(1) \) was defined in (20). Equivalently, or any \( f \in \mathcal{K} \) we have

\[ \beta f(\lambda) = D\left(k^{-1}(\lambda)\right) f\left(k^{-1}(\lambda)\right) = D(\lambda) f\left(k^{-1}(\lambda)\right), \] (29)

since \( D(\lambda) \) is \( k \) invariant. \( \beta \) is a unitary operator in \( \mathcal{K} \) with the inverse given by

\[ \beta^{-1} \phi \lambda = \frac{1}{D\left(k^{-1}(\lambda)\right)} \phi_{k^{-1}(\lambda)}, \]

or, equivalently, for any \( f \in \mathcal{K} \)

\[ \beta^{-1} f(\lambda) = \frac{1}{D(\lambda)} f(k(\lambda)). \]

Conjugation with \( \beta \) gives an automorphism \( \alpha \) of \( \mathfrak{A} \) since one verifies that

\[ \alpha(U_\lambda) := \beta U_\lambda \beta^{-1} = D(\lambda) U_{k(\lambda)}. \] (30)

In fact,

\[ \beta U_\lambda \beta^{-1} \phi_\mu = \frac{1}{D\left(k^{-1}(\mu)\right)} \beta U_\lambda \phi_{k^{-1}(\mu)} = \frac{r(\lambda, k^{-1}(\mu))}{D\left(k^{-1}(\mu)\right)} \beta \phi_{k^* \mu}, \]

\[ = \frac{r(\lambda, k^{-1}(\mu)) D(\lambda) \phi_{k^{-1}(\mu)}}{D\left(k^{-1}(\mu)\right)} \phi_{k(\lambda) k^{-1}(\mu)} = \frac{r(\lambda, k^{-1}(\mu)) D(\lambda) \phi_{k^{-1}(\mu)}}{D\left(k^{-1}(\mu)\right)} \phi_{k(\lambda) k^{-1}(\mu)}. \]

Notice that by (27) we have

\[ U_{k(\lambda) \phi_\mu} = r(k(\lambda), \mu) \phi_{k(\lambda) k^{-1}(\mu)}. \]

Consequently,

\[ \beta U_\lambda \beta^{-1} \phi_\mu = \frac{r(\lambda, k^{-1}(\mu)) D(\lambda) \phi_{k^{-1}(\mu)}}{D\left(k^{-1}(\mu)\right) r(k(\lambda), \mu)} U_{k(\lambda) \phi_\mu} = D(\lambda) U_{k(\lambda) \phi_\mu} \]

by (22).

Define

\[ \tau(A) := (\phi_1, A \phi_1) \]

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Since $\beta \phi_1 = \phi_1$, the state $\tau$ is $\alpha$ invariant. Moreover vector $\phi_1$ is cyclic and separating for $\mathfrak{A}$ and so the GNS Hilbert space of state $\tau$ is canonically identified with $\mathcal{K}$. In this identification $U_\lambda$ is mapped to $\phi_\lambda$ and the unitary operator in $\mathcal{K}$ defined by $\alpha$ is simply $\beta$.

We need to verify that the system $(\mathfrak{A}, \mathbb{Z}, \alpha, \tau)$ is totally ergodic and that its quantum quasi-spectrum $(H_1(\alpha), H_2(\alpha), [r], k_\alpha, k_\alpha)$ is isomorphic to $(H_1, H_2, [r], k)$. It follows from (29) that the spectrum of $\beta$ (and equivalently of $\alpha$) is $H_1$ with $\phi_\lambda$, $\lambda \in H_1$ being the corresponding eigenvectors. Also

$$\beta^n f(\lambda) = D(\lambda)^n f \left( R(\lambda)^{-n} \ast \lambda \right),$$

where $R(\lambda) := k(\lambda) \ast \lambda^{-1} \in H_1$. As $H_1$ has no nontrivial elements of finite order, $\phi_1$ is the only invariant vector for $\beta^n$ and $\alpha$ is totally ergodic. Next observe that

$$\alpha(U_\lambda) = \frac{D(\lambda) U_{R(\lambda)}}{r(R(\lambda), \lambda)} U_\lambda,$$

and so that $H_2(\alpha)$ consists of the operators of the form $\frac{D(\lambda) U_{R(\lambda)}}{r(R(\lambda), \lambda)}$. They are different for different $\lambda$'s as they correspond to different quasi-eigenvectors of an ergodic system. The map

$$H_2 \ni \lambda \mapsto \phi(\lambda) := \frac{D(\lambda) U_{R(\lambda)}}{r(R(\lambda), \lambda)} \in H_2(\alpha)$$

is consequently bijective. $\phi$ is a homomorphism as a consequence of the following calculation:

$$\phi(\lambda \ast \mu) U_{\lambda \ast \mu} = \alpha(U_{\lambda \ast \mu}) = \frac{1}{r(\lambda, \mu)} \alpha(U_\lambda U_\mu) = \frac{1}{r(\lambda, \mu)} \alpha(U_\lambda) \alpha(U_\mu)$$

$$= \frac{1}{r(\lambda, \mu)} \phi(\lambda) U_\lambda \phi(\mu) U_\mu = \frac{1}{r(\lambda, \mu)} \phi(\lambda) \ast \phi(\mu) U_\lambda U_\mu = \phi(\lambda) \ast \phi(\mu) U_{\lambda \ast \mu}$$

Since $R(\phi(\lambda)) = R(\lambda)$, it follows that $k = \phi^{-1} k_\alpha \phi$. Finally, as $\{\phi_\lambda\}$ is a normalized basis in $\mathcal{K}$ consisting of quasi-eigenvectors of $\alpha$, formula (27) implies that $[r] = \phi^*[r_\alpha]$. □

VI. Example: Quantum Torus

Consider the following dynamics on a quantum torus. Recall that the algebra $\mathfrak{A}$ of observables on a quantum torus is defined as the universal von Neumann algebra generated by two unitary generators $U, V$ satisfying the relation $[R]$:

$$UV = e^{2\pi i h} VU.$$
One can think of the elements of $\mathfrak{A}$ as series of the form $a = \sum a_{n,m} U^n V^m$. A natural trace on $\mathfrak{A}$ is simply given by $\tau(a) = a_{0,0}$. The automorphism $\alpha$ is defined on generators by:

$$\alpha(U) := e^{2\pi i \omega} U, \quad \alpha(V) := UV.$$ 

It extends to an automorphism of $\mathfrak{A}$. If $\omega$ is irrational, then $\alpha$ is totally ergodic. In fact, the eigenvectors of $\alpha$ are just powers of $U$:

$$\alpha(U^n) = e^{2\pi i \omega} U^n.$$ 

Consequently $H_1 = \{e^{2\pi i \omega}, \ n \in \mathbb{Z}\} \cong \mathbb{Z}$ and the spectrum is simple which proves total ergodicity if $\omega$ is irrational. Moreover

$$\alpha(U^n V^m) = e^{2\pi i (n\omega + hm(m-1)/2)} U^n V^m,$$

which shows that $U^n V^m$ are quasi-eigenvectors of the second order for $\alpha$. Since they form an orthonormal basis in $L^2(\mathfrak{A}, \tau)$ we see that $(\mathfrak{A}, G, \alpha, \tau)$ is a totally ergodic system with purely quasi-discrete spectrum of the second order.

We can identify $H_2 \cong \mathbb{Z}^2$ as groups and $H_1$ is simply the subgroup $\mathbb{Z} \times \{0\} \subset \mathbb{Z}^2$. The mapping $R$ is given by

$$R(n, m) = m \in \mathbb{Z} \cong H_1,$$

and the isomorphism $k$ is

$$k(n, m) = (n + m, m).$$

Define

$$C(n, m) := \left\{ \begin{array}{cl}
1 & \text{if } m = 0 \\
\frac{1}{e^{2\pi i (h(mn-n) + \omega n^2/m-n)}} & \text{otherwise}
\end{array} \right.$$ 

Then a simple calculation shows that $C(n, m) U^n V^m$ is a normalized basis for this ergodic system.

In this simple example the group $H_2$ is abelian. We can identify $H^2_k(H_2)$ with $H^2(H_2)$, the second cohomology group of $H_2$. The later group is identified with the set of symplectic bicharacters by (24). A simple calculation shows that the following symplectic bicharacter represents $[r]$ in our example.

$$\sigma ((n, m), (n', m')) = e^{2\pi i h(mn'-n'm)},$$

Notice that $\sigma$ is trivial on $H_1$ and $k$-invariant.

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