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Sequence entropy and rigid σ-algebras

by

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Abstract. We study relationships between sequence entropy and the Kronecker and rigid algebras. Let $(Y, \mathcal{Y}, \nu, T)$ be a factor of a measure-theoretical dynamical system $(X, \mathcal{X}, \mu, T)$ and S be a sequence of positive integers with positive upper density. We prove there exists a subsequence $A \subseteq S$ such that $h_\mu^A(T, \xi \mid \mathcal{Y}) = H_\mu(\xi \mid \mathcal{K}(X \mid Y))$ for all finite partitions ξ, where $\mathcal{K}(X \mid Y)$ is the Kronecker algebra over $\mathcal{Y}$. A similar result holds for rigid algebras over $\mathcal{Y}$. As an application, we characterize compact, rigid and mixing extensions via relative sequence entropy.

1. Introduction. Sequence entropy for a measure was introduced as an isomorphism invariant by Kushnirenko [Ku], who used it to distinguish between transformations with the same entropy. It is also a spectral invariant. Kushnirenko [Ku] proved that an invertible measure-preserving transformation has discrete spectrum if and only if the sequence entropy of the system is zero for any sequence. Later, sequence entropy was mainly used to characterize different kinds of mixing properties in [S, Hu1, Hu2, Z1, Z2, HSY]. Also, in [BD, KY] relations between large sets of integers and mixing properties were considered.

The purpose of this paper is to study the relationship between sequence entropy and some important σ-algebras associated to a measure-theoretical dynamical system, namely the Kronecker and rigid algebras, and their relative versions.

Let $(X, \mathcal{X}, \mu, T)$ be a measure-theoretical dynamical system. It is not difficult to prove by using standard properties of entropy and the Pinsker σ-algebra that given a finite measurable partition ξ,

$$\lim_{n\to\infty} h_\mu(T^n, \xi) = H_\mu(\xi \mid \Pi(X)),$$

where $\Pi(X)$ is the Pinsker σ-algebra of the system (see [P] for general properties and [B-R] for an explicit proof). One can restate this result using

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the language of sequence entropy as follows:

$$\sup_{A=n\mathbb{Z}_+,\, n\in\mathbb{N}} h_\mu^A(T,\xi) = H_\mu(\xi \mid \Pi(X)).$$

What happens if one takes the supremum over another increasing sequence A of positive integers? It was shown in [HMY] that

$$\max_{A\subseteq\mathbb{Z}_+} h_\mu^A(T,\xi) = H_\mu(\xi \mid \mathcal{K}(X)), \tag{1.1}$$

where $\mathcal{K}(X)$ is the Kronecker algebra of the system and ξ is any finite measurable partition.

In this paper we address the previous question for conditinal sequence entropy with respect to a factor. Let $(Y,\mathcal{Y},\nu,T)$ be a factor of $(X,\mathcal{X},\mu,T)$.

First we show in Section 3 (Theorem 3.4) that for any given increasing sequence S of positive integers with positive upper density,

$$\max_{A\subseteq S} h_\mu^A(T,\xi \mid \mathcal{Y}) = H_\mu(\xi \mid \mathcal{K}(X \mid Y))$$

for any finite measurable partition ξ, where $\mathcal{K}(X \mid Y)$ is the Kronecker algebra relative to $\mathcal{Y}$. As a corollary (Corollary 3.5) we sligthly extend (1.1) by proving that

$$\max_{A\subseteq S} h_\mu^A(T,\xi) = H_\mu(\xi \mid \mathcal{K}(X)).$$

Then in Section 4 we consider rigid algebras associated to the system relative to the factor. We prove (Theorem 4.11) that for any IP-set F' there exists an IP-subset F of F' such that

$$\max\{h_\mu^A(T,\xi \mid \mathcal{Y}) : A \subseteq F \text{ is } \mathcal{F}\text{-monotone}\} = H_\mu(\xi \mid \mathcal{K}_F(X \mid Y)) \tag{1.2}$$

for all finite measurable partitions ξ, where $\mathcal{K}_F(X \mid Y)$ is the rigid algebra relative to $\mathcal{Y}$ along F (refer to Section 4 for related concepts). The analogue of (1.1) for rigid algebras is given in Corollary 4.13.

Two applications of the above results are presented.

The first one is a characterization of compact and weakly mixing extensions and rigid and mildly mixing extensions via conditional sequence entropy, providing new proofs and slightly more general statements for results in [Hu1, Hu2] and [Z1, Z2] respectively.

The other application is given in Section 5. We show that $\max_A\{h_\mu^A(T \mid \mathcal{Y})\} \in \{\log k : k \in \mathbb{N}\} \cup \{\infty\}$.

In Section 2 we give some basic concepts and results in ergodic theory and entropy theory.

2. Preliminaries. In this article, the integers, non-negative integers, natural numbers and complex numbers are denoted by $\mathbb{Z}$, $\mathbb{Z}_+$, $\mathbb{N}$ and $\mathbb{C}$ respectively.

2.1. *Basic concepts.* Let $(X, \mathcal{X}, \mu)$ be a standard Borel space with μ a regular probability measure on X and let $T : X \to X$ be an invertible measure-preserving transformation. The quadruple $(X, \mathcal{X}, \mu, T)$ is called a *measure-theoretical dynamical system*, or just *system*, if $T\mu = \mu$, that is, $\mu(B) = \mu(T^{-1}B)$ for all $B \in \mathcal{X}$. For simplicity, in what follows all transformations of the system are called T.

A system $(X, \mathcal{X}, \mu, T)$ is *ergodic* if any measurable set $A \in \mathcal{X}$ for which $\mu(A \triangle T^{-1}A) = 0$ has $\mu(A) = 0$ or $\mu(A) = 1$. A system $(X, \mathcal{X}, \mu, T)$ is *weakly mixing* if $(X \times X, \mathcal{X} \otimes \mathcal{X},\ \mu \otimes \mu,\ T \times T)$ is ergodic; and it is *strongly mixing* if $\lim_{n\to\infty} \mu(T^{-n}A \cap B) = \mu(A)\mu(B)$ for any $A, B \in \mathcal{X}$.

A system $(Y, \mathcal{Y}, \nu, T)$ is a *factor* of $(X, \mathcal{X}, \mu, T)$ if there exists a measurable map $\pi : X \to Y$ such that $\pi\mu = \nu$ and $\pi \circ T = T \circ \pi$. Equivalently one says that $(X, \mathcal{X}, \mu, T)$ is an *extension* of $(Y, \mathcal{Y}, \nu, T)$.

Let $(Y, \mathcal{Y}, \nu, T)$ be a factor of $(X, \mathcal{X}, \mu, T)$. One can identify $L^2(Y, \mathcal{Y}, \nu)$ with the subspace $L^2(X, \pi^{-1}(\mathcal{Y}), \mu)$ of $L^2(X, \mathcal{X}, \mu)$ via $f \mapsto f \circ \pi$. By using this identification one can define the projection of $L^2(X, \mathcal{X}, \mu)$ onto $L^2(Y, \mathcal{Y}, \nu)$: $f \mapsto \mathbb{E}(f \mid \mathcal{Y})$. The *conditional expectation* $\mathbb{E}(f \mid \mathcal{Y})$ is characterized as the unique $\mathcal{Y}$-measurable function in $L^2(Y, \mathcal{Y}, \nu)$ such that

$$\int_Y g\mathbb{E}(f \mid \mathcal{Y})\, d\nu = \int_X g \circ \pi f\, d\mu \tag{2.1}$$

for all $g \in L^2(Y, \mathcal{Y}, \nu)$.

The *disintegration* of μ over ν is given by a measurable map $y \mapsto \mu_y$ from Y to the space of probability measures on X such that

$$\mathbb{E}(f \mid \mathcal{Y})(y) = \int_X f\, d\mu_y \tag{2.2}$$

ν-almost everywhere.

The *self-joining of* $(X, \mathcal{X}, \mu, T)$ *relatively independent over the factor* $(Y, \mathcal{Y}, \nu, T)$ is the system $(X \times X, \mathcal{X} \otimes \mathcal{X}, \mu \times_Y \mu, T \times T)$, where the measure $\mu \times_Y \mu$ is defined by

$$\mu \times_Y \mu(B) = \int_Y \mu_y \times \mu_y(B)\, d\nu(y), \qquad \forall B \in \mathcal{X} \otimes \mathcal{X}. \tag{2.3}$$

This measure is characterized by

$$\int_{X\times X} f_1 \otimes f_2\, d\mu \times_Y \mu = \int_Y \mathbb{E}(f_1 \mid \mathcal{Y})\mathbb{E}(f_2 \mid \mathcal{Y})\, d\nu \tag{2.4}$$

for all $f_1, f_2 \in L^2(X, \mathcal{X}, \mu)$, where $f_1 \otimes f_2(x_1, x_2) = f_1(x_1)f_2(x_2)$.

For details about the concepts in this subsection see [F1, G].

2.2. *Kronecker systems and rigid systems.* Let $(X, \mathcal{X}, \mu, T)$ be a system. An *eigenfunction* of T is a non-zero complex-valued function $f \in L^2(X, \mathcal{X}, \mu)$ such that $Tf = \lambda f$ for some $\lambda \in \mathbb{C}$, where $Tf = f \circ T$. The complex number λ is called the *eigenvalue of T associated to f*. If $f \in L^2(X,\mathcal{X},\mu)$ is an eigenfunction of T, then $\mathrm{cl}\{T^n f : n \in \mathbb{Z}\}$ is a compact subset of $L^2(X,\mathcal{X},\mu)$. In general, one says that f is *compact* if $\mathrm{cl}\{T^n f : n \in \mathbb{Z}\}$ is compact in $L^2(X,\mathcal{X},\mu)$. Let $H_c(T)$ be the set of all compact functions in $L^2(X,\mathcal{X},\mu)$. It is well known that $H_c(T)$ is the closure of the set spanned by all the eigenfunctions of T.

The following proposition is a classical result (see for example [Zi]).

PROPOSITION 2.1. *Let $(X,\mathcal{X},\mu,T)$ be a system and H be an algebra of bounded functions in $L^2(X,\mathcal{X},\mu)$ which is invariant under complex conjugation. Then there exists a sub-σ-algebra $\mathcal{A}$ of $\mathcal{X}$ such that* $\mathrm{cl}(H) = L^2(X,\mathcal{A},\mu)$. *Moreover, if H is T-invariant, then $\mathcal{A}$ is T-invariant.*

One easily deduces from Proposition 2.1 that there exists a T-invariant sub-σ-algebra $\mathcal{K}(X)$ of $\mathcal{X}$ such that $H_c(T) = L^2(X,\mathcal{K}(X),\mu)$. $\mathcal{K}(X)$ is called the *Kronecker algebra* of $(X,\mathcal{X},\mu,T)$. The system $(X,\mathcal{X},\mu,T)$ is said to be *compact* or to have *discrete spectrum* if $H_c(T) = L^2(X,\mathcal{X},\mu)$ or equivalently $\mathcal{K}(X) = \mathcal{X}$.

A function $f \in L^2(X,\mathcal{X},\mu)$ is *rigid* if there exists an increasing sequence $\{t_n\}_{n\in\mathbb{N}} \subseteq \mathbb{Z}_+$ with $\lim_{n\to\infty} T^{t_n} f = f$ in $L^2(X,\mathcal{X},\mu)$. For a fixed sequence $F = \{t_n\}_{n\in\mathbb{N}} \subseteq \mathbb{Z}_+$, $H_F(T)$ denotes the set of all functions $f \in L^2(X,\mathcal{X},\mu)$ with $\lim_{n\to\infty} T^{t_n} f = f$ in $L^2(X,\mathcal{X},\mu)$. It is easy to see that the set of all bounded functions in $H_F(T)$ forms a T-invariant subalgebra of $L^2(X,\mathcal{X},\mu)$, invariant under complex conjugation. Thus from Proposition 2.1 one deduces that there exists a T-invariant sub-σ-algebra $\mathcal{K}_F(X)$ of $\mathcal{X}$ such that $H_F(T) = L^2(X,\mathcal{K}_F(X),\mu)$. A system $(X,\mathcal{X},\mu,T)$ is called *rigid* if there is $F = \{t_n\}_{n\in\mathbb{N}} \subseteq \mathbb{Z}_+$ such that $H_F(T) = L^2(X,\mathcal{X},\mu)$.

2.3. *Mixing properties and filters.* A system $(X,\mathcal{X},\mu,T)$ is *mildly mixing* if it does not have non-constant rigid functions. In the strongly mixing case $\mathcal{K}_F(X)$ is trivial for any sequence F, thus strong mixing implies mild mixing. Also, since every eigenfunction is rigid, mild mixing implies weak mixing. It can be proved that mild mixing lies strictly between weak mixing and strong mixing [FW]. For more details on mixing properties see [F1, F2, W2].

An upward hereditary collection $\mathcal{G}$ of subsets of $\mathbb{Z}_+$ is said to be a *family*. That is, subsets of $\mathbb{Z}_+$ containing elements of $\mathcal{G}$ are in $\mathcal{G}$ too. If a family $\mathcal{G}$ is closed under finite intersections and satisfies $\emptyset \notin \mathcal{G}$, then it is called a *filter*. The *dual* of a family $\mathcal{G}$ is $\mathcal{G}^* = \{F \subseteq \mathbb{Z}_+ : F \cap F' \neq \emptyset \text{ for all } F' \in \mathcal{F}\}$.

Now some important families are introduced. Let A be a subset of either $\mathbb{Z}_+$ or $\mathbb{Z}$. The *upper Banach density of A* is

$$d^*(A) = \limsup_{|I|\to\infty} \frac{|A \cap I|}{|I|},$$

where I ranges over all intervals of $\mathbb{Z}_+$ or $\mathbb{Z}$ and $|\cdot|$ denotes cardinality. The *upper density* of a subset A of $\mathbb{Z}_+$ is

$$\bar{d}(A) = \limsup_{N\to\infty} \frac{|A \cap \{0,\dots,N-1\}|}{N};$$

if A is subset of $\mathbb{Z}$, then

$$\bar{d}(A) = \limsup_{N\to\infty} \frac{|A \cap \{-N,\dots,N\}|}{2N+1}.$$

The *lower Banach density* $d_*(A)$ and the *lower density* $\underline{d}(A)$ are defined analogously, with lim inf. If $\bar{d}(A) = \underline{d}(A)$, then one says that A has *density* $d(A)$. Let $\mathcal{D} = \{A \subseteq \mathbb{Z}_+ : d(A) = 1\}$ and $\mathcal{BD} = \{A : d_*(A) = 1\}$. It is easy to see that $\mathcal{D}$ and $\mathcal{BD}$ are filters with duals $\mathcal{D}^* = \{A \subseteq \mathbb{Z}_+ : \bar{d}(A) > 0\}$ and $\mathcal{BD}^* = \{A : d^*(A) > 0\}$ respectively.

Let $\{b_i\}_{i\in I}$ be a finite or infinite sequence in $\mathbb{N}$. Define

$$\mathrm{FS}(\{b_i\}_{i\in I}) = \Big\{\sum_{i\in\alpha} b_i : \alpha \text{ is a finite non-empty subset of } I\Big\}.$$

A set $F \subset \mathbb{Z}_+$ is an IP-*set* if there exists a sequence $\{b_i\}_{i\in\mathbb{N}}$ of natural numbers such that $F = \mathrm{FS}(\{b_i\}_{i\in\mathbb{N}})$. Denote the set of all IP-sets by $\mathcal{IP}$.

Let $\{x_n\}_{n\in\mathbb{Z}_+}$ be a sequence in a metric space (X,d), $x \in X$, and $\mathcal{G}$ be a family. One says that x_n *$\mathcal{G}$-converges to x*, denoted by $\mathcal{G}\text{-}\lim x_n = x$, if for any neighborhood U of x, $\{n \in \mathbb{Z}_+ : x_n \in U\} \in \mathcal{G}$. The following is a well known result concerning mixing in ergodic theory (see [F1, F2]).

THEOREM 2.2. *Let $(X,\mathcal{X},\mu,T)$ be a system. Then*:

(1) *T is weakly mixing if and only if $\mathcal{D}\text{-}\lim \mu(T^{-n}A \cap B) = \mu(A)\mu(B)$ for any $A, B \in \mathcal{X}$;*
(2) *T is mildly mixing if and only if $\mathcal{IP}^*\text{-}\lim \mu(T^{-n}A \cap B) = \mu(A)\mu(B)$ for any $A, B \in \mathcal{X}$.*

For more discussion about various kinds of mixing and families, refer to [BD, KY].

2.4. *Sequence entropy and conditional sequence entropy.* Let $(X,\mathcal{X},\mu,T)$ be a system and $S = \{t_i\}_{i\in\mathbb{N}}$ be an increasing sequence of non-negative integers. Let ξ be a measurable partition and $\mathcal{A}$ a sub-σ-algebra of $\mathcal{X}$. The (*Shannon*) *entropy of ξ* and the (*Shannon*) *entropy of ξ given $\mathcal{A}$* are given respectively by

$$H_\mu(\xi) = -\sum_{A\in\xi} \mu(A)\log\mu(A)$$

and

$$H_\mu(\xi \mid \mathcal{A}) = \sum_{A\in\xi} \int_X -\mathbb{E}(1_A \mid \mathcal{A}) \log \mathbb{E}(1_A \mid \mathcal{A})\, d\mu.$$

One also uses the notation $\mu(A \mid \mathcal{A}) = \mathbb{E}(1_A \mid \mathcal{A})$.

Let ξ, η be measurable partitions with $H_\mu(\xi \,|\, \mathcal{A}), H_\mu(\eta \,|\, \mathcal{A}) < \infty$ and identify (when necessary) η with the σ-algebra it induces. It is known that $H_\mu(\xi \,|\, \mathcal{A})$ increases with respect to ξ and decreases with respect to $\mathcal{A}$, and

$$H_\mu(\xi \vee \eta \,|\, \mathcal{A}) = H_\mu(\xi \,|\, \eta \vee \mathcal{A}) + H_\mu(\eta \,|\, \mathcal{A}).$$

DEFINITION 2.3. The *conditional sequence entropy along S of ξ given $\mathcal{A}$* in the system $(X, \mathcal{X}, \mu, T)$ is defined by

$$\begin{aligned} h_\mu^S(T, \xi \,|\, \mathcal{A}) &= \limsup_{n\to\infty} \frac{1}{n} H_\mu\Big(\bigvee_{i=1}^{n} T^{-t_i}\xi \,\Big|\, \mathcal{A}\Big) \\ &= \limsup_{n\to\infty} \frac{1}{n} \sum_{j=2}^{n} H_\mu\Big(T^{-t_j}\xi \,\Big|\, \bigvee_{i=1}^{j-1} T^{-t_i}\xi \vee \mathcal{A}\Big). \end{aligned}$$

The *conditional sequence entropy along S given $\mathcal{A}$* in the system $(X, \mathcal{X}, \mu, T)$ is

$$h_\mu^S(T \,|\, \mathcal{A}) = \sup_\xi \{h_\mu^S(T, \xi \,|\, \mathcal{A}) : H_\mu(\xi \,|\, \mathcal{A}) < \infty\}.$$

When $S = \mathbb{Z}_+$ and $\mathcal{A}$ is trivial one recovers the entropy of T with respect to μ.

Let $(Y, \mathcal{Y}, \nu, T)$ be a factor of $(X, \mathcal{X}, \mu, T)$ and $\{\mu_y\}_{y\in Y}$ be the disintegration of μ over ν. Then the conditional (Shannon) entropy of ξ given $\mathcal{Y}$ can be represented as

$$H_\mu(\xi \,|\, \mathcal{Y}) = \int_Y H_y(\xi)\, d\nu, \tag{2.5}$$

where $H_y(\cdot)$ denotes the entropy with respect to μ_y and $\mathcal{Y}$ is viewed as a sub-σ-algebra of $\mathcal{X}$. The following two lemmas come from [Hu2].

LEMMA 2.4. *Let ξ and η be measurable partitions of X with $H_\mu(\xi \,|\, \mathcal{Y})$, $H_\mu(\eta \,|\, \mathcal{Y}) < \infty$. Then*

$$|h_\mu^S(T, \xi \,|\, \mathcal{Y}) - h_\mu^S(T, \eta \,|\, \mathcal{Y})| \le \int_Y (H_y(\xi \,|\, \eta) + H_y(\eta \,|\, \xi))\, d\nu$$

for any increasing sequence $S \subseteq \mathbb{Z}_+$.

LEMMA 2.5. *There exists a countable set $\{\xi_n\}_{n\in\mathbb{N}}$ of finite measurable partitions of X such that*

$$\inf_n \Big\{ \int_Y (H_y(\xi \,|\, \xi_n) + H_y(\xi_n \,|\, \xi))\, d\nu \Big\} = 0$$

for all measurable partitions ξ with $H_\mu(\xi \,|\, \mathcal{Y}) < \infty$.

Hence one has

$$h_\mu^S(T \,|\, \mathcal{Y}) = \sup_\xi \{h_\mu^S(T, \xi \,|\, \mathcal{Y}) : \xi \text{ is finite}\}.$$

Thus $h_\mu^S(T \mid \mathcal{Y}) = 0$ if and only if $h_\mu^S(T, \xi \mid \mathcal{Y}) = 0$ for all two-set measurable partitions ξ, since every finite partition is a refinement of two-set partitions.

For more information about entropy theory refer to [G, P, W1].

3. Sequence entropy relative to the compact extension. Throughout this section we fix a system $(X, \mathcal{X}, \mu, T)$ and a factor $(Y, \mathcal{Y}, \nu, T)$.

3.1. *Almost periodic functions.* The $L^2(X, \mathcal{X}, \mu)$ norm is denoted by $\|\cdot\|$ and the $L^2(X, \mathcal{X}, \mu_y)$ norm by $\|\cdot\|_y$ for ν-almost every $y \in Y$. The corresponding inner products are denoted by $\langle\cdot,\cdot\rangle$ and $\langle\cdot,\cdot\rangle_y$. Recall $\{\mu_y\}_{y\in Y}$ is the disintegration of μ over ν.

DEFINITION 3.1. A function $f \in L^2(X, \mathcal{X}, \mu)$ is *almost periodic over* $\mathcal{Y}$ if for every $\varepsilon > 0$ there exist $g_1, \dots, g_l \in L^2(X, \mathcal{X}, \mu)$ such that for all $n \in \mathbb{Z}$,

$$\min_{1\le j\le l} \|T^n f - g_j\|_y < \varepsilon$$

for ν-almost every $y \in Y$. One writes $f \in \mathrm{AP}(\mathcal{Y})$.

REMARK 3.2.

(1) The almost periodic functions over $\mathcal{Y}$ form a subspace of $L^2(X, \mathcal{X}, \mu)$. Using Proposition 2.1 one can verify that there exists a sub-σ-algebra $\mathcal{K}(X \mid Y)$ of $\mathcal{X}$ such that $\overline{\mathrm{AP}(\mathcal{Y})} = L^2(X, \mathcal{K}(X \mid Y), \mu)$.

(2) One calls $\mathcal{K}(X \mid Y)$ *the Kronecker algebra over* $\mathcal{Y}$. Any function $f \in \overline{\mathrm{AP}(\mathcal{Y})}$ is called a *compact function over* $\mathcal{Y}$.

The following theorem will be used later.

THEOREM 3.3 ([Hu2]). *Let $f \in L^2(X, \mathcal{X}, \mu)$. Then $f \in L^2(X, \mathcal{K}(X \mid Y), \mu)^\perp$ if and only if*

$$\lim_{n\to\infty} \frac{1}{n} \sum_{i=0}^{n-1} |\mathbb{E}(gT^i f \mid \mathcal{Y})| = 0$$

in $L^1(Y, \mathcal{Y}, \nu)$ for all $g \in L^2(X, \mathcal{X}, \mu)$.

3.2. *Conditional sequence entropy and $\mathcal{K}(X \mid Y)$.* In this section we will prove the following result.

THEOREM 3.4. *Let $(X, \mathcal{X}, \mu, T)$ be a system and $(Y, \mathcal{Y}, \nu, T)$ be its factor. Then for every increasing sequence $S \in \mathcal{D}^*$,*

$$\max_{A\subseteq S} h_\mu^A(T, \xi \mid \mathcal{Y}) = H_\mu(\xi \mid \mathcal{K}(X \mid Y)) \tag{3.1}$$

for all measurable partitions ξ of X with $H_\mu(\xi \mid \mathcal{Y}) < \infty$.

The following result is now immediate.

COROLLARY 3.5 ([HMY]). *Let $(X,\mathcal{X},\mu,T)$ be a system. Then for every increasing sequence $S\in\mathcal{D}^*$,*

$$\max_{A\subseteq S} h_\mu^A(T,\xi)=H_\mu(\xi\,|\,\mathcal{K}(X)) \tag{3.2}$$

for all measurable partitions ξ of X with $H_\mu(\xi)<\infty$.

Observe that our result is more general than the one in [HMY], where it is only proved that $\max_{A\subseteq\mathbb{Z}_+} h_\mu^A(T,\xi)=H_\mu(\xi\,|\,\mathcal{K}(X))$.

Theorem 3.4 follows directly from the following series of lemmas.

LEMMA 3.6. *For any increasing sequence $S\in\mathcal{D}^*$ there exists a subsequence $A\subseteq S$ such that*

$$h_\mu^A(T,\xi\,|\,\mathcal{Y})\ge H_\mu(\xi\,|\,\mathcal{K}(X\,|\,Y)) \tag{3.3}$$

for any measurable partition ξ of X with $H_\mu(\xi\,|\,\mathcal{Y})<\infty$.

Proof. To simplify notation, $\mathcal{K}(X\,|\,Y)$ is denoted by $\mathcal{K}$. First, we prove the following claim.

CLAIM. *Given finite measurable partitions ξ and η of X and $\epsilon>0$, there exist a sequence $D\in\mathcal{D}$ and $M\in\mathbb{N}$ such that for any $m\ge M$ in D,*

$$\int_Y H_y(T^{-m}\xi\,|\,\eta)\,d\nu\ge H_\mu(\xi\,|\,\mathcal{K})-\epsilon. \tag{3.4}$$

Proof of the Claim. Let $\xi=\{A_1,\dots,A_k\}$ and $\eta=\{B_1,\dots,B_l\}$. For any $A,B\in\mathcal{X}$, since $1_A-\mathbb{E}(1_A\,|\,\mathcal{K})\in L^2(X,\mathcal{K},\mu)^\perp$, by Theorem 3.3 one has

$$\lim_{n\to\infty}\frac{1}{n}\sum_{i=0}^{n}\Big|\int_X T^i(1_A-\mathbb{E}(1_A\,|\,\mathcal{K}))1_B\,d\mu_y\Big|=0$$

in $L^1(Y,\mathcal{Y},\nu)$. Equivalently, there exists $D'=D'(A,B)\in\mathcal{D}$ such that

$$\lim_{D'\ni n\to\infty}\int_Y\Big|\int_X T^n(1_A-\mathbb{E}(1_A\,|\,\mathcal{K}))1_B\,d\mu_y\Big|\,d\nu=0.$$

Since $\mathcal{D}$ is a filter, there exists $D\in\mathcal{D}$ such that for any $1\le i\le k, 1\le j\le l$,

$$\lim_{D\ni n\to\infty}\int_Y\Big|\mu_y(T^{-n}A_i\cap B_j)-\int_X T^n\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y\Big|\,d\nu=0. \tag{3.5}$$

Let $\varphi(x)=-x\log x$. Choose $0<\delta<\frac{\epsilon}{4}\frac{1}{kl\log l}$ such that

$$|u-v|<\delta\ \Rightarrow\ |\varphi(u)-\varphi(v)|<\frac{\epsilon}{4}\frac{1}{kl}.$$

By (3.5) there exists $M>0$ such that for every $m>M$ in D there is $E_m\subseteq Y$ with $\nu(E_m)>1-\epsilon/(2\log k)$ such that

$$\Big|\mu_y(T^{-m}A_i\cap B_j)-\int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y\Big|<\delta$$

for all $1\le i\le k, 1\le j\le l$ and $y\in E_m$.

For any $y \in E_m$,

$$\begin{aligned}
&\Big|\sum_{i,j} -\mu_y(T^{-m}A_i \cap B_j)\log\frac{\mu_y(T^{-m}A_i\cap B_j)}{\mu_y(B_j)} \\
&\qquad + \Big(\int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y\Big)\log\frac{\int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y}{\mu_y(B_j)}\Big| \\
&\le \sum_{i,j}\Big|\mu_y(T^{-m}A_i\cap B_j)\log\mu_y(T^{-m}A_i\cap B_j) \\
&\qquad - \int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y \log\int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y\Big| \\
&\qquad + \sum_i\Big|\sum_j\Big(\mu_y(T^{-m}A_i\cap B_j) - \int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y\Big)\log\mu_y(B_j)\Big| \\
&\le kl\,\frac{\epsilon}{4}\,\frac{1}{kl} + k\delta\Big|\log\Big(\prod_j \mu_y(B_j)\Big)\Big| \le \frac{\epsilon}{4} + k\,\frac{\epsilon}{4}\,\frac{1}{kl\log l}\Big|\log\Big(\frac{\sum_j\mu_y(B_j)}{l}\Big)^l\Big| = \frac{\epsilon}{2}.
\end{aligned}$$

Hence

$$\begin{aligned}
&H_y(T^{-m}\xi\,|\,\eta) \\
&\quad = \sum_{i,j} -\mu_y(T^{-m}A_i\cap B_j)\log\frac{\mu_y(T^{-m}A_j\cap B_j)}{\mu_y(B_j)} \\
&\quad \ge \sum_{i,j}\Big(-\int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y\Big)\log\frac{\int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y}{\mu_y(B_j)} - \frac{\epsilon}{2}
\end{aligned}$$

Let

$$a_{ij} = -\Big(\int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y\Big)\log\frac{\int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})1_{B_j}\,d\mu_y}{\mu_y(B_j)}.$$

Then we have $a_{ij} = \mu_y(B_j)\varphi(\int_{B_j} T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})\,d\mu_{B_j,y})$, where $\mu_{B_j,y} = \mu_y(\cdot\cap B_j)/\mu_y(B_j)$. Since φ is concave, one deduces

$$\begin{aligned}
a_{ij} &\ge \mu_y(B_j)\int_{B_j} -T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})\log T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})\,d\mu_{B_j,y} \\
&= \int_{B_j} -T^m\mathbb{E}(1_{A_i}|\mathcal{K})\log T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})\,d\mu_y.
\end{aligned}$$

Thus

$$H_y(T^{-m}\xi\,|\,\eta) \ge \sum_{i,j} a_{ij} - \frac{\epsilon}{2} \ge \sum_i\int_X -T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})\log T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K})\,d\mu_y - \frac{\epsilon}{2}.$$

Integrating with respect to ν one obtains

$$\begin{aligned}\int_Y H_y(T^{-m}\xi \mid \eta)\, d\nu &\geq \int_{E_m} H_y(T^{-m}\xi \mid \eta)\, d\nu \\ &\geq \sum_i \int_{E_m}\int_X -T^m\mathbb{E}(1_{A_i} \mid \mathcal{K}) \log T^m\mathbb{E}(1_{A_i} \mid \mathcal{K})\, d\mu_y\, d\nu - \frac{\epsilon}{2} \\ &= \sum_i \int_Y\int_X -T^m\mathbb{E}(1_{A_i} \mid \mathcal{K}) \log T^m\mathbb{E}(1_{A_i} \mid \mathcal{K})\, d\mu_y\, d\nu \\ &\quad - \sum_i \int_{Y\setminus E_m}\int_X -T^m\mathbb{E}(1_{A_i} \mid \mathcal{K}) \log T^m\mathbb{E}(1_{A_i} \mid \mathcal{K})\, d\mu_y\, d\nu - \frac{\epsilon}{2} \\ &\geq \sum_i \int_X -T^m\mathbb{E}(1_{A_i} \mid \mathcal{K}) \log T^m\mathbb{E}(1_{A_i} \mid \mathcal{K})\, d\mu - \frac{\epsilon}{2\log k}\log k - \frac{\epsilon}{2} \\ &= H_\mu(\xi \mid \mathcal{K}) - \epsilon.\end{aligned}$$

In the last inequality we use $\int_X \sum_i -T^m\mathbb{E}(1_{A_i} \mid \mathcal{K}) \log T^m\mathbb{E}(1_{A_i} \mid \mathcal{K})\, d\mu_y = H_y(T^{-m}\xi \mid \mathcal{K}) \leq \log k$. This completes the proof of the claim.

Let $\{\xi_k\}_{k\in\mathbb{N}}$ be as in Lemma 2.5. For any increasing sequence $S \in \mathcal{D}^*$, since $\mathcal{D}$ is a filter, one can choose $A = \{t_1 < t_2 < \cdots\} \subseteq S$ such that

$$\int_Y H_y\Big(T^{-t_n}\xi_j \,\Big|\, \bigvee_{i=1}^{n-1} T^{-t_i}\xi_j\Big)\, d\nu \geq H_\mu(\xi_j \mid \mathcal{K}) - \frac{1}{2^n} \quad \text{for any } n\geq 2 \text{ and } 1\leq j\leq n.$$

Fix $k \in \mathbb{N}$. One has

$$\begin{aligned}&h_\mu^A(T, \xi_k \mid \mathcal{Y}) \\ &\quad= \limsup_{n\to\infty} \frac{1}{n} H_\mu\Big(\bigvee_{i=1}^n T^{-t_i}\xi_k \,\Big|\, \mathcal{Y}\Big) = \limsup_{n\to\infty} \frac{1}{n}\int_Y H_y\Big(\bigvee_{i=1}^n T^{-t_i}\xi_k\Big)\, d\nu \\ &\quad= \limsup_{n\to\infty} \frac{1}{n}\int_Y \Big[H_y\Big(\bigvee_{i=1}^k T^{-t_i}\xi_k\Big) + \sum_{i=k+1}^n H_y\Big(T^{-t_i}\xi_k \,\Big|\, \bigvee_{j=1}^{i-1} T^{-t_j}\xi_k\Big)\Big]\, d\nu \\ &\quad\geq \limsup_{n\to\infty} \frac{1}{n}\Big[\int_Y H_y\Big(\bigvee_{i=1}^k T^{-t_i}\xi_k\Big)\, d\nu + (n-k)H_\mu(\xi_k \mid \mathcal{K}) - \sum_{i=k+1}^n \frac{1}{2^i}\Big] \\ &\quad= H_\mu(\xi_k \mid \mathcal{K}).\end{aligned}$$

Therefore $h_\mu^A(T, \xi_k \mid \mathcal{Y}) \geq H_\mu(\xi_k \mid \mathcal{K})$ for any $k \in \mathbb{N}$. Now let ξ be any partition with $H(\xi \mid \mathcal{Y}) < \infty$. Given $\delta > 0$, by Lemma 2.5 one can choose ξ_k such that $\int_Y (H_y(\xi \mid \xi_k) + H_y(\xi_k \mid \xi))\, d\nu < \delta$. Then $|h_\mu^A(T, \xi \mid \mathcal{Y}) - h_\mu^A(T, \xi_k \mid \mathcal{Y})| < \delta$ and $|H_\mu(\xi \mid \mathcal{Y}) - H_\mu(\xi_k \mid \mathcal{Y})| < \delta$. So

$$h_\mu^A(T, \xi \mid \mathcal{Y}) \geq h_\mu^A(T, \xi_k \mid \mathcal{Y}) - \delta \geq H_\mu(\xi \mid \mathcal{Y}) - 2\delta.$$

Since δ is arbitrary, the proof is complete. ■

LEMMA 3.7. *Let $B\in\mathcal{X}$. Then $B\in\mathcal{K}(X\,|\,Y)$ if and only if $h_\mu^A(T,\{B,B^c\}\,|\,\mathcal{Y}) = 0$ for any increasing sequence $A\subseteq\mathbb{Z}_+$.*

Proof. For necessity we refer to [Hu2, Theorem 1]. To prove sufficiency we will use Lemma 3.6. If $B\notin\mathcal{K}(X\,|\,Y)$ then $H_\mu(\{B,B^c\}\,|\,\mathcal{K}(X\,|\,Y))>0$. Thus, by Lemma 3.6, there exists $A\subseteq\mathbb{Z}_+$ such that

$$h_\mu^A(T,\{B,B^c\}\,|\,\mathcal{Y})\ge H_\mu(\{B,B^c\}\,|\,\mathcal{K}(X\,|\,Y))>0. \ \blacksquare$$

LEMMA 3.8. *For any measurable partition ξ of X with $H_\mu(\xi\,|\,\mathcal{Y})<\infty$ and any increasing sequence $A\subseteq\mathbb{Z}_+$,*

$$h_\mu^A(T,\xi\,|\,\mathcal{Y})\le H_\mu(\xi\,|\,\mathcal{K}(X\,|\,Y)). \tag{3.6}$$

Proof. Let $\{\xi_k\}_{k\in\mathbb{N}}$ be a countable set of finite $\mathcal{K}(X\,|\,Y)$-measurable partitions such that $\xi_k\nearrow\mathcal{K}(X\,|\,Y)$. Let $A=\{t_1<t_2<\cdots\}$. Since ξ_k is $\mathcal{K}(X\,|\,Y)$-measurable, by Lemma 3.7 one has $h_\mu^A(T,\xi_k\,|\,\mathcal{Y})=0$. So

$$\begin{aligned}
h_\mu^A(T,\xi\,|\,\mathcal{Y}) &= \limsup_{n\to\infty}\frac{1}{n}\int_Y H_y\Big(\bigvee_{i=1}^n T^{-t_i}\xi\Big)\,d\nu - h_\mu^A(T,\xi_k\,|\,\mathcal{Y})\\
&\le \limsup_{n\to\infty}\frac{1}{n}\int_Y H_y\Big(\bigvee_{i=1}^n T^{-t_i}(\xi\vee\xi_k)\Big)\,d\nu - \lim_{n\to\infty}\frac{1}{n}\int_Y H_y\Big(\bigvee_{i=1}^n T^{-t_i}\xi_k\Big)\,d\nu\\
&= \limsup_{n\to\infty}\frac{1}{n}\int_Y\Big(H_y\Big(\bigvee_{i=1}^n T^{-t_i}(\xi\vee\xi_k)\Big)-H_y\Big(\bigvee_{i=1}^n T^{-t_i}\xi_k\Big)\Big)\,d\nu\\
&= \limsup_{n\to\infty}\frac{1}{n}\int_Y H_y\Big(\bigvee_{i=1}^n T^{-t_i}\xi\,\Big|\,\bigvee_{i=1}^n T^{-t_i}\xi_k\Big)\,d\nu\\
&\le \limsup_{n\to\infty}\frac{1}{n}\int_Y\sum_{i=1}^n H_y(T^{-t_i}\xi\,|\,T^{-t_i}\xi_k)\,d\nu\\
&= \limsup_{n\to\infty}\frac{1}{n}\int_Y\sum_{i=1}^n H_y(\xi\,|\,\xi_k)\,d\nu\\
&= \int_Y H_y(\xi\,|\,\xi_k)\,d\nu = \int_Y (H_y(\xi\vee\xi_k)-H_y(\xi_k))\,d\nu\\
&= H_\mu(\xi\vee\xi_k\,|\,\mathcal{Y})-H_\mu(\xi_k\,|\,\mathcal{Y}) = H_\mu(\xi\,|\,\xi_k\vee\mathcal{Y})\le H_\mu(\xi\,|\,\xi_k).
\end{aligned}$$

One concludes by the martingale theorem. ∎

3.3. *Compact and weakly mixing extensions.* Now as a corollary of the last subsection we recover some results of Hulse [Hu1, Hu2]. First let us recall some notations.

Definition 3.9.

(1) $(X,\mathcal{X},\mu,T)$ is called a *compact extension* of $(Y,\mathcal{Y},\nu,T)$ if
$$L^2(X,\mathcal{K}(X\,|\,Y),\mu)=L^2(X,\mathcal{X},\mu),\quad \text{that is,}\quad \mathcal{K}(X\,|\,Y)=\mathcal{X}.$$
(2) $(X,\mathcal{X},\mu,T)$ is called a *weakly mixing extension* of $(Y,\mathcal{Y},\nu,T)$ if $\mathcal{K}(X\,|\,Y)=\mathcal{Y}$.

Remark 3.10. For a more complete discussion of compact and weakly mixing extensions see [F1, Hu2]. For example, in [Hu2] it is proved that $(X,\mathcal{X},\mu,T)$ is a weakly mixing extension of $(Y,\mathcal{Y},\nu,T)$ if and only if $(X\times X,\mathcal{X}\otimes\mathcal{X},\mu\times_Y\mu,T\times T)$ is ergodic relative to $(Y,\mathcal{Y},\nu,T)$ if and only if $\lim_{n\to\infty}n^{-1}\sum_{i=0}^{n-1}|\mathbb{E}(gT^if\,|\,\mathcal{Y})|=0$ in $L^1(Y,\mathcal{Y},\nu)$ for all $f\in L^2(X,\mathcal{X},\mu)$ and $g\in L^2(X,\mathcal{Y},\mu)^\perp$ (here we view $\mathcal{Y}$ as a sub-σ-algebra of $\mathcal{X}$).

The results of the last subsection immediately yield

Corollary 3.11 ([Hu2]).

(1) $(X,\mathcal{X},\mu,T)$ *is a compact extension of* $(Y,\mathcal{Y},\nu,T)$ *if and only if* $h_\mu^A(T\,|\,\mathcal{Y})=0$ *for any increasing sequence* $A\subseteq\mathbb{Z}_+$.
(2) $(X,\mathcal{X},\mu,T)$ *is a weakly mixing extension of* $(Y,\mathcal{Y},\nu,T)$ *if and only if for any increasing sequence* $S\in\mathcal{D}^*$, *there exists an increasing subsequence* $A\subseteq S$ *such that* $h_\mu^A(T,\xi\,|\,\mathcal{Y})=H_\mu(\xi\,|\,\mathcal{Y})$ *for all measurable partitions* ξ *of* X *with* $H_\mu(\xi\,|\,\mathcal{Y})<\infty$.

Observe that the second statement is a little stronger than the corresponding result in [Hu2]. The case when $\mathcal{Y}$ is trivial can be found in [Hu1].

4. Sequence entropy relative to a rigid extension

4.1. $\mathcal{F}$*-sequence and* IP*-systems.* Let $\mathcal{F}$ denote the collection of all non-empty finite subsets of $\mathbb{N}$. Given $\alpha,\beta\in\mathcal{F}$, we write $\alpha<\beta$ (or $\beta>\alpha$) if $\max\alpha<\min\beta$. The set
$$\mathcal{F}^{(1)}=\mathrm{FU}(\{\alpha_i\}_{i\in\mathbb{N}}):=\Big\{\bigcup_{i\in\beta}\alpha_i:\beta\in\mathcal{F}\Big\}$$
with $\alpha_1<\alpha_2<\cdots$ is called an *IP-ring.* The following theorem will be useful.

Theorem 4.1 (Hindman's Theorem). *For any finite partition* $\{C_1,\dots,C_r\}$ *of* $\mathcal{F}$ *one of the* C_i*'s contains an* IP*-ring.*

Let $\{n_i\}_{i\in\mathbb{N}}\subseteq\mathbb{Z}_+$. Set $n_\alpha=\sum_{i\in\alpha}n_i$ for $\alpha\in\mathcal{F}$. Then $\mathrm{FS}(\{n_i\}_{i\in\mathbb{N}})=\{n_\alpha\}_{\alpha\in\mathcal{F}}$ and the IP-set generated by this sequence is $\mathrm{FS}(\{n_i\}_{i\in\mathbb{N}})$. Observe that we do not require the elements of $\{n_i\}_{i\in\mathbb{N}}$ to be distinct. If $\mathcal{F}^{(1)}$ is an IP-ring of $\mathcal{F}$, then $\{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$ is an IP-subset of $\{n_\alpha\}_{\alpha\in\mathcal{F}}$; conversely, any IP-subset of $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ has this form.

A sequence in any space Y indexed by the set $\mathcal{F}$ is called an *$\mathcal{F}$-sequence*. If Y is a (multiplicative) semigroup, then an $\mathcal{F}$-sequence $\{y_\alpha\}_{\alpha\in\mathcal{F}}$ on Y defines an IP-*system* if $y_\alpha = y_{i_1}\cdots y_{i_k}$ for any $\alpha = \{i_1,\ldots,i_k\}\in\mathcal{F}$ with $i_1<\cdots<i_k$. An IP-system should be viewed as a generalized semigroup. Indeed, if $\alpha\cap\beta=\emptyset$ and $\alpha<\beta$ then $y_{\alpha\cup\beta}=y_\alpha y_\beta$.

Let $\mathcal{F}^{(1)}$ be an IP-ring. Then the map $\xi:\mathcal{F}\to\mathcal{F}^{(1)}$, $\xi(\alpha)=\bigcup_{i\in\alpha}\alpha_i$, is bijective and structure-preserving in the sense that $\xi(\alpha\cup\beta)=\xi(\alpha)\cup\xi(\beta)$. In particular, any sequence $\{y_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$ can be naturally identified with a particular $\mathcal{F}$-sequence, namely $\{x_\alpha\}_{\alpha\in\mathcal{F}}$ where $x_\alpha=y_{\xi(\alpha)}$.

Definition 4.2. Assume that $\{x_\alpha\}_{\alpha\in\mathcal{F}}$ is an $\mathcal{F}$-sequence in a topological space X. Let $x\in X$ and $\mathcal{F}^{(1)}$ be an IP-ring. Write

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} x_\alpha = x$$

if for any neighborhood U of x there exists $\alpha_0\in\mathcal{F}^{(1)}$ such that $x_\alpha\in U$ for any $\alpha\in\mathcal{F}^{(1)}$ with $\alpha>\alpha_0$.

Theorem 4.3 ([FK]). *Let $\{U_\alpha\}_{\alpha\in\mathcal{F}}$ be an* IP-*system of unitary operators on a separable Hilbert space $\mathcal{H}$. Then there is an* IP-*subsystem $\{U_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$, with $\mathcal{F}^{(1)}$ an* IP-*ring, such that*

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} U_\alpha = P$$

weakly, where P is the orthogonal projection onto a subspace of $\mathcal{H}$.

4.2. *Almost periodicity over $\mathcal{Y}$ along $\mathcal{F}^{(1)}$.* Let $(X,\mathcal{X},\mu,T)$ be a system and $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ be an IP-set. Then $\{T^{n_\alpha}\}_{\alpha\in\mathcal{F}}$ and $\{(T\times T)^{n_\alpha}\}_{\alpha\in\mathcal{F}}$ define IP-systems. One writes $T_\alpha=T^{n_\alpha}$ and $(T\times T)_\alpha=(T\times T)^{n_\alpha}$.

Now consider a factor $(Y,\mathcal{Y},\nu,T)$ of $(X,\mathcal{X},\mu,T)$ and let $\pi:X\to Y$ be the corresponding factor map. By Theorem 4.3, there exists an IP-ring $\mathcal{F}^{(1)}\subseteq\mathcal{F}$ such that for all $K\in L^2(X\times X,\mathcal{X}\otimes\mathcal{X},\mu\times_Y\mu)$,

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}}(T\times T)_\alpha K = PK \tag{4.1}$$

exists in the weak topology and P is an orthogonal projection.

Definition 4.4. Let $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ be an IP-set and $\mathcal{F}^{(1)}\subseteq\mathcal{F}$ an IP-ring. A function $f\in L^2(X,\mathcal{X},\mu)$ is called *almost periodic over $\mathcal{Y}$ with respect to $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ along $\mathcal{F}^{(1)}$*, and one writes $f\in\mathrm{AP}(\mathcal{Y},\{n_\alpha\},\mathcal{F}^{(1)})$, if for every $\varepsilon>0$ there exists a set $D\in\mathcal{Y}$ with $\nu(D)<\varepsilon$ and functions $g_1,\ldots,g_l\in L^2(X,\mathcal{X},\mu)$ such that for every $\delta>0$ there exists $\alpha_0\in\mathcal{F}^{(1)}$ with the property that whenever $\alpha\in\mathcal{F}^{(1)}$ with $\alpha>\alpha_0$ there is a set $E_\alpha\in\mathcal{Y}$ with $\nu(E_\alpha)<\delta$ such that for all $y\notin D\cup E_\alpha$,

$$\min_{1\le j\le l}\|T_\alpha f-g_j\|_y<\varepsilon.$$

Remark 4.5.

(1) The definition we use comes from [BM], and is different from those in [FK] and [Z2]. In [FK] a function is called almost periodic over $\mathcal{Y}$ with respect to $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ along $\mathcal{F}^{(1)}$ if for every $\varepsilon > 0$ and $\alpha_0 \in \mathcal{F}^{(1)}$ there exist $g_1, \ldots, g_l \in L^2(X, \mathcal{X}, \mu)$ and a set $E \subseteq \mathcal{Y}$ with $\nu(E) < \varepsilon$ such that for all $\alpha \in \mathcal{F}^{(1)}$ with $\alpha > \alpha_0$ and $y \notin E$ one has $\min_{1\le j\le l} \|T_\alpha f - g_j\|_y < \varepsilon$. Refer to [BM] for a discussion of the difference between the two definitions.

(2) $\mathrm{AP}(\mathcal{Y}, \{n_\alpha\}, \mathcal{F}^{(1)})$ need not be closed, but if $f \in \overline{\mathrm{AP}(\mathcal{Y}, \{n_\alpha\}, \mathcal{F}^{(1)})}$, then for every $\varepsilon > 0$ there exist $g_1, \ldots, g_l \in L^\infty(X, \mathcal{X}, \mu)$ and $\alpha_0 \in \mathcal{F}^{(1)}$ such that for any $\alpha \in \mathcal{F}^{(1)}$ with $\alpha > \alpha_0$, there is a set $E_\alpha \in \mathcal{Y}$ with $\nu(E_\alpha) < \varepsilon$ and $\min_{1\le j\le l} \|T_\alpha f - g_j\|_y < \varepsilon$ for all $y \notin E_\alpha$.

(3) $\mathrm{AP}(\mathcal{Y}, \{n_\alpha\}, \mathcal{F}^{(1)}) \cap L^\infty(X, \mathcal{X}, \mu)$ is a T-invariant σ-algebra which contains $|g|$ and $\bar{g}$ whenever it contains g. By Proposition 2.1, there exists a sub-σ-algebra $\mathcal{K}_F(X \mid Y)$, where $F = \{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$, such that (see also [FK, Lemma 7.3])

$$\overline{\mathrm{AP}(\mathcal{Y}, \{n_\alpha\}, \mathcal{F}^{(1)})} = L^2(X, \mathcal{K}_F(X \mid Y), \mu). \tag{4.2}$$

(4) One calls $\mathcal{K}_F(X \mid Y)$ a *rigid algebra over* $\mathcal{Y}$, and any function $f \in \overline{\mathrm{AP}(\mathcal{Y}, \{n_\alpha\}, \mathcal{F}^{(1)})}$ is called a *rigid function over* $\mathcal{Y}$.

To each $K \in L^2(X \times X, \mathcal{X} \otimes \mathcal{X}, \mu \times_Y \mu)$ and ν-almost every $y \in Y$ we associate an operator (also called) $K : L^2(X, \mathcal{X}, \mu_y) \to L^2(X, \mathcal{X}, \mu_y)$, $f \mapsto K * f$, where

$$K * f(x) = \int_X K(x, x') f(x')\, d\mu_y(x'), \quad \text{where } y = \pi(x). \tag{4.3}$$

For ν-a.e. $y \in Y$, K is a Hilbert–Schmidt operator on $L^2(X, \mathcal{X}, \mu_y)$. In particular, it is a compact operator (i.e. the closure of the image of the unit ball is compact). See [F1, FK] for details.

For the next four results fix a system $(X, \mathcal{X}, \mu, T)$, a factor $(Y, \mathcal{Y}, \nu, T)$ of it, an IP-set $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ and an IP-ring $\mathcal{F}^{(1)}$ such that (4.1) holds. Let $F = \{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$ and let $\mathcal{K}_F(X \mid Y)$ be the associated rigid algebra over $\mathcal{Y}$.

Lemma 4.6. *If $K \in L^2(X \times X, \mathcal{X} \otimes \mathcal{X}, \mu \times_Y \mu)$ with $PK = K$ and $f \in L^\infty(X, \mathcal{X}, \mu)$, then $K * f \in \mathrm{AP}(\mathcal{Y}, \{n_\alpha\}, \mathcal{F}^{(1)})$.*

Proof. Let $\varepsilon > 0$. Since for ν-a.e. $y \in Y$ the operator K is compact on $L^2(X, \mathcal{X}, \mu_y)$, there exists $M(y) \in \mathbb{N}$ such that the set

$$\{K * (T^j f) : -M(y) \le j \le M(y)\}$$

is $\varepsilon/2$-dense in $\{K * (T^j f) : j \in \mathbb{Z}\}$ (in $L^2(X, \mathcal{X}, \mu_y)$). Let M be large enough such that $M > M(y)$ for all y outside of a set $D \in \mathcal{Y}$ with $\nu(D) < \varepsilon$ and let

$$\{g_1, \ldots, g_l\} = \{K * (T^j f) : -M \le j \le M\}.$$

Then for any $y \in D^c$ and any $n \in \mathbb{Z}$,

$$\inf_{1\le j\le l} \|K * (T^n f) - g_j\|_y < \varepsilon/2. \tag{4.4}$$

On the other hand, by (4.1) one has

$$\begin{aligned}
&\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \|T_\alpha(K * f) - K * (T_\alpha f)\|^2 \\
&\quad= \text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \int_X \Big| \int_X (K(T_\alpha x, T_\alpha x') - K(x,x'))f(T_\alpha x')\, d\mu_{\pi(x)}(x')\Big|^2 d\mu(x) \\
&\quad\le \text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \int_X \int_X |K(T_\alpha x, T_\alpha x') - K(x,x')|^2 |f(T_\alpha x')|^2\, d\mu_{\pi(x)}(x')\, d\mu(x) \\
&\quad\le \text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \|(T\times T)_\alpha K - K\|^2 \|f\|_\infty^2 = 0.
\end{aligned}$$

So for any $\delta > 0$ there exists $\alpha_0 \in \mathcal{F}^{(1)}$ such that for any $\alpha \in \mathcal{F}^{(1)}$ with $\alpha > \alpha_0$ there is a set $E_\alpha \in \mathcal{Y}$ with $\nu(E_\alpha) < \delta$ and for any $y \notin E_\alpha$,

$$\|T_\alpha(K * f) - K * (T_\alpha f)\|_y < \varepsilon/2. \tag{4.5}$$

Hence whenever $y \notin D \cup E_\alpha$, one has

$$\inf_{1\le j\le l} \|T_\alpha(K * f) - g_j\|_y < \varepsilon. \ \blacksquare \tag{4.6}$$

THEOREM 4.7. *Let $(X, \mathcal{X}, \mu, T)$, $(Y, \mathcal{Y}, \nu, T)$, $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ and $\mathcal{F}^{(1)}$ be as above. Then $f \in L^2(X, \mathcal{K}_F(X \mid Y), \mu)^\perp$ if and only if*

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \int_Y |\,\mathbb{E}(gT_\alpha f \mid \mathcal{Y})|\, d\nu = 0$$

for any $g \in L^2(X, \mathcal{X}, \mu)$.

Proof. Assume that $f \in L^2(X, \mathcal{K}_F(X \mid Y), \mu)^\perp$. Then

$$\begin{aligned}
&\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \Big(\int_Y |\mathbb{E}(gT_\alpha f \mid \mathcal{Y})|\, d\nu\Big)^2 \le \text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \int_Y \Big|\mathbb{E}(gT_\alpha f \mid \mathcal{Y})\Big|^2 d\nu \\
&\quad= \text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \int_{X\times X} g\otimes \overline{g}\cdot (T\times T)_\alpha (f\otimes \overline{f})\, d\mu\times_Y \mu \\
&\quad= \int_{X\times X} g\otimes \overline{g} P(f\otimes \overline{f})\, d\mu \times_Y \mu = \int_{X\times X} f\otimes \overline{f} P(g\otimes \overline{g})\, d\mu\times_Y \mu.
\end{aligned}$$

Let $K = P(g \otimes \overline{g})$. Then $PK = K$ and

$$\begin{aligned}\int\limits_{X\times X} f \otimes \bar{f} P(g\otimes \overline{g}) d\mu \times_Y \mu &= \int\limits_{X\times X} f\otimes \bar{f} K d\mu \times_Y \mu \\ &= \int\limits_Y \int\limits_{X\times X} f(x)\bar{f}(x')K(x,x')\, d\mu_y(x)\, d\mu_y(x')\, d\nu(y) \\ &= \int\limits_X f(x) \int\limits_X K(x,x')\bar{f}(x')\, d\mu_{\pi(x)}(x')\, d\mu(x) \\ &= \int\limits_X f(x) K * \bar{f}(x)\, d\mu(x) = \langle \bar{f}, K * \bar{f}\rangle.\end{aligned}$$

By Lemma 4.6, $K * \bar{f} \in \overline{\mathrm{AP}(\mathcal{Y}, \{n_\alpha\}, \mathcal{F}^{(1)})}$. So $\langle \bar{f}, K*\bar{f}\rangle = 0$. Hence

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \int |\mathbb{E}(gT_\alpha f \mid \mathcal{Y})|\, d\nu = 0.$$

Now we show the converse. It suffices to show that if $f\in L^2(X,\mathcal{K}_F(X\mid Y),\mu)$ and $\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \int_Y |\mathbb{E}(gT_\alpha f \mid \mathcal{Y})|\, d\nu = 0$ for any $g \in L^2(X,\mathcal{X},\mu)$, then $f = 0$. The method follows from [BM, Lemma 3.13.] and [FK, Lemma 7.6].

Let $0 < \delta < 1$ be so small that for any $h \in L^2(X,\mathcal{X},\mu)$ satisfying $\|f - h\|^2 < 2\delta$ one has $|\langle f,h\rangle| > \|f\|^2/2$. Let $\varepsilon > 0$ with $\varepsilon^2 < \delta$ and $\int_E \|f\|_y^2\, d\nu < \delta$ for all $E \in \mathcal{Y}$ with $\nu(E) < \varepsilon$.

By Remark 4.5(2), for $f \in L^2(X,\mathcal{K}_F(X\mid Y),\mu) = \overline{\mathrm{AP}(\mathcal{Y}, \{n_\alpha\}, \mathcal{F}^{(1)})}$, there exist $g_1,\dots,g_l \in L^\infty(X,\mathcal{X},\mu)$ and $\alpha_0 \in \mathcal{F}^{(1)}$ such that whenever $\alpha \in \mathcal{F}^{(1)}$ with $\alpha > \alpha_0$ there is a set $E_\alpha \in \mathcal{Y}$ with $\nu(E_\alpha) < \varepsilon$ satisfying: for all $y \notin E_\alpha$ there exists $j(\alpha,y)$ with $1 \le j(\alpha,y) \le l$ such that

$$\|T_\alpha f - g_{j(\alpha,y)}\|_y < \varepsilon.$$

For every $\alpha \in \mathcal{F}^{(1)}$ with $\alpha > \alpha_0$ and $i \in \{1,\dots,l\}$, let $\xi_i(y) = 1$ if $y \notin E_\alpha$ and $j(\alpha,y) = i$, and $\xi_i(y) = 0$ otherwise. Write $h_\alpha = \sum_{i=1}^l \xi_i g_i$, that is, h_α is equal to $g_{j(\alpha,y)}$ on the fiber over y when $y \notin E_\alpha$, and equal to zero on fibers over $y \in E_\alpha$. Each h_α is measurable and

$$\begin{aligned}\|f - T_\alpha^{-1}h_\alpha\|^2 = \|T_\alpha f - h_\alpha\|^2 &= \int\limits_Y \int\limits_X |T_\alpha f - h_\alpha|^2\, d\mu_y(x)\, d\nu \\ &= \int\limits_{E_\alpha} \|T_\alpha f\|_y^2\, d\nu + \int\limits_{Y\setminus E_\alpha} \|T_\alpha f - g_{j(\alpha,y)}\|_y^2\, d\nu \le \delta + \varepsilon^2 \le 2\delta.\end{aligned}$$

Hence $|\langle T_\alpha f, h_\alpha\rangle| = |\langle f, T_\alpha^{-1}h_\alpha\rangle| \ge \|f\|^2/2$. Also,

$$\begin{aligned}|\langle T_\alpha f, h_\alpha\rangle| &= \Big|\sum_{j=1}^l \int\limits_Y \xi_j(y) \int\limits_X T_\alpha f \cdot \overline{g}_j\, d\mu_y\, d\nu\Big| \\ &\le \sum_{j=1}^l \int\limits_Y \Big| \int\limits_X T_\alpha f \cdot \overline{g}_j\, d\mu_y\Big|\, d\nu = \sum_{j=1}^l \int\limits_Y |\mathbb{E}(T_\alpha f \cdot \overline{g}_j \mid \mathcal{Y})|\, d\nu.\end{aligned}$$

Since IP-$\lim_{\alpha\in\mathcal{F}^{(1)}}\int_Y |\mathbb{E}(gT_\alpha f\,|\,\mathcal{Y})|d\nu = 0$ for any $g\in L^2(X,\mathcal{X},\mu)$, it follows that $\|f\|=0$ and thus $f=0$. ∎

Proposition 4.8. *We have $f\in L^2(X,\mathcal{K}_F(X\,|\,Y),\mu)$ if and only if for any $\varepsilon>0$ and any* IP*-ring $\mathcal{F}^{(2)}=\mathrm{FU}(\{\alpha_i\}_{i\in\mathbb{N}})\subseteq\mathcal{F}^{(1)}$, there is $M\in\mathbb{N}$ such that for every $\alpha\in\mathcal{F}^{(2)}$ with $\alpha>\alpha_M$ there exists $E_\alpha\in\mathcal{Y}$ with $\nu(E_\alpha)<\varepsilon$ satisfying, for any $y\notin E_\alpha$,*

$$\inf_{\beta\in\mathrm{FU}(\{\alpha_i\}_{i=1}^M)}\|T_\alpha f-T_\beta f\|_y<\varepsilon.$$

Proof. Let $f\in L^2(X,\mathcal{K}_F(X\,|\,Y),\mu)$. By Remark 4.5(2), for any $\varepsilon>0$ there exist $g_1,\dots,g_l\in L^\infty(X,\mathcal{X},\mu)$ and $\alpha_0\in\mathcal{F}^{(1)}$ such that for any $\alpha\in\mathcal{F}^{(1)}$ with $\alpha>\alpha_0$, there is $E'_\alpha\in\mathcal{Y}$ with $\nu(E'_\alpha)<\varepsilon/2$ satisfying

$$\inf_{1\le j\le l}\|T_\alpha f-g_j\|_y<\varepsilon/2 \tag{4.7}$$

for any $y\notin E'_\alpha$. Without loss of generality, assume $\alpha_1<\alpha_2<\cdots$. Let $M_1\in\mathbb{N}$ be such that $\alpha_{M_1}>\alpha_0$.

For $j\in\{1,\dots,l\}$ let $E_j=\{y\in Y:\|T_\alpha f-g_j\|_y<\varepsilon/2$ for some $\alpha\in\mathcal{F}^{(2)}\}$. Then we can assume that $\nu(E_j)=1$ for all $1\le j\le l$, otherwise we may modify g_j so that $g_j=T_{\alpha_{M_1}}f$ on $\pi^{-1}(E_j^c)$ without affecting (4.7).

For $j\in\{1,\dots,l\}$ let $E_{j,n}=\{y\in Y:\|T_\beta f-g_j\|_y<\varepsilon/2$ for some $\beta\in\mathrm{FU}(\{\alpha_i\}_{i=1}^n)\}$. Then $\nu(\bigcup_{n\ge1}E_{j,n})=1$ for all $1\le j\le l$. Thus there is $M_2\in\mathbb{N}$ such that $\nu(\bigcap_{j=1}^l E_{j,n})>1-\varepsilon/2$ for any $n\ge M_2$. Let $M=\max\{M_1,M_2\}$. Then for any $\alpha\in\mathcal{F}^{(2)}$ with $\alpha>\alpha_M$ (that is, $\alpha\in\mathrm{FU}(\{\alpha_i\}_{i>M})$)

$$\inf_{\beta\in\mathrm{FU}(\{\alpha_i\}_{i=1}^M)}\|T_\alpha f-T_\beta f\|_y\le\inf_{1\le j\le l}\{\|T_\alpha f-g_j\|_y+\inf_{\beta\in\mathrm{FU}(\{\alpha_i\}_{i=1}^M)}\|T_\beta f-g_j\|_y\}<\varepsilon$$

for all y not in $E_\alpha=E'_\alpha\cup(\bigcap_{j=1}^l E_{j,M})^c$, which has measure less than ε.

Now we show the converse. If $f\notin L^2(X,\mathcal{K}_F(X\,|\,Y),\mu)$, then $f=f_1+f_2$, where $f_1\in L^2(X,\mathcal{K}_F(X\,|\,Y),\mu)$ and $f_2\in L^2(X,\mathcal{K}_F(X\,|\,Y),\mu)^\perp$ with f_2 non-trivial. One deduces that there is $\varepsilon>0$ such that $\|f_2\|_y^2\ge3\varepsilon$ for any y in a set $E\in\mathcal{Y}$ of measure greater than 2ε.

By Theorem 4.7, IP-$\lim_{\alpha\in\mathcal{F}^{(1)}}\int_Y|\mathbb{E}(gT_\alpha f_2\,|\,\mathcal{Y})|\,d\nu=0$ for any $g\in L^2(X,\mathcal{X},\mu)$. Fix any IP-ring $\mathcal{F}^{(2)}=\mathrm{FU}(\{\alpha_i\}_{i\in\mathbb{N}})\subseteq\mathcal{F}^{(1)}$ and $M\in\mathbb{N}$. Since

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}}\int\limits_Y|\mathbb{E}(T_\beta\bar f_2T_\alpha f_2\,|\,\mathcal{Y})|\,d\nu=0$$

for any $\beta\in\mathrm{FU}(\{\alpha_i\}_{i=1}^M)$, there is $\alpha_{M'}\in\mathcal{F}^{(2)}$, $M'>M$, such that for any $\alpha\in\mathcal{F}^{(2)}$ with $\alpha>\alpha_{M'}$, there exists $A_\alpha\in\mathcal{Y}$ with $\nu(A_\alpha)>1-\varepsilon$ such that $|\langle T_\alpha f_2,T_\beta f_2\rangle_y|<\varepsilon$ for any $y\in A_\alpha$. Then

$$\|T_\alpha f_2-T_\beta f_2\|_y^2=\|T_\alpha f_2\|_y^2+\|T_\beta f_2\|_y^2-2\mathrm{Re}\langle T_\alpha f_2,T_\beta f_2\rangle_y>\varepsilon>\varepsilon^2$$

for any $y\in T_\alpha^{-1}E\cap A_\alpha$, the measure of which is $\nu(T_\alpha^{-1}E\cap A_\alpha)>\varepsilon$.

So for any $\alpha \in \mathcal{F}^{(2)}$ with $\alpha > \alpha_{M'}$, one has

$$\nu\{y \in Y : \inf_{\beta \in \mathrm{FU}(\{\alpha_i\}_{i=1}^M)} \|T_\alpha f - T_\beta f\|_y^2 < \varepsilon^2\}$$
$$\leq \nu\{y \in Y : \inf_{\beta \in \mathrm{FU}(\{\alpha_i\}_{i=1}^M)} \|T_\alpha f_2 - T_\beta f_2\|_y^2 < \varepsilon^2\} < 1 - \varepsilon.$$

This contradicts the assumption of the proposition. ■

Definition 4.9. Let $\{n_\alpha\}_{\alpha \in \mathcal{F}}$ be an IP-set and $\mathcal{F}^{(1)}$ and IP-ring. Any subset having the form

$$\{n_{\beta_i}\}_{i \in \mathbb{N}} \subseteq \{n_\alpha\}_{\alpha \in \mathcal{F}^{(1)}} \tag{4.8}$$

with $\beta_1 < \beta_2 < \cdots$ is called an *$\mathcal{F}$-monotone subset* of $\{n_\alpha\}_{\alpha \in \mathcal{F}^{(1)}}$.

A proof similar to that of Proposition 4.8 yields the following corollary.

Corollary 4.10. *$f \in L^2(X, \mathcal{K}_F(X \mid Y), \mu)$ if and only if for any any $\varepsilon > 0$ and any $\mathcal{F}$-monotone subset $\{n_{\beta_i}\}_{i \in \mathbb{N}} \subseteq \{n_\alpha\}_{\alpha \in \mathcal{F}^{(1)}}$ there exists $M \in \mathbb{N}$ such that for every $n \in \mathbb{N}$ with $n > M$ there is $E_n \in \mathcal{Y}$ with $\nu(E_n) < \varepsilon$ satisfying, for any $y \notin E_n$,*

$$\inf_{1 \leq i \leq n-1} \|T_{\beta_n} f - T_{\beta_i} f\|_y < \varepsilon.$$

4.3. *Conditional sequence entropy and rigid algebra $\mathcal{K}_F(X \mid Y)$.* As in the previous section, in this subsection we study relations between conditional sequence entropy and the rigid algebra $\mathcal{K}_F(X \mid Y)$. The main result is the following.

Theorem 4.11. *Let $(X, \mathcal{X}, \mu, T)$ be a system and $(Y, \mathcal{Y}, \nu, T)$ one of its factors. For any* IP*-set $\{n_\alpha\}_{\alpha \in \mathcal{F}}$ there exists an* IP*-ring $\mathcal{F}^{(1)}$ of $\mathcal{F}$ such that for any* IP*-ring $\mathcal{F}^{(2)} \subseteq \mathcal{F}^{(1)}$ there exists an $\mathcal{F}$-monotone subset $A \subseteq \{n_\alpha\}_{\alpha \in \mathcal{F}^{(2)}}$ such that*

$$h_\mu^A(T, \xi \mid \mathcal{Y}) = H_\mu(\xi \mid \mathcal{K}_F(X \mid Y)) \tag{4.9}$$

for all measurable partitions ξ of X with $H_\mu(\xi \mid \mathcal{Y}) < \infty$, where $F = \{n_\alpha\}_{\alpha \in \mathcal{F}^{(1)}}$.

In particular, for any IP*-set $\{n_\alpha\}_{\alpha \in \mathcal{F}}$ there exists an* IP*-ring $\mathcal{F}^{(1)}$ of $\mathcal{F}$ such that*

$$\max\{h_\mu^A(T, \xi \mid \mathcal{Y}) : A \subseteq F \text{ is } \mathcal{F}\text{-monotone}\} = H_\mu(\xi \mid \mathcal{K}_F(X \mid Y)), \tag{4.10}$$

where $F = \{n_\alpha\}_{\alpha \in \mathcal{F}^{(1)}}$.

Remark 4.12. The reason why we need to consider the given IP-set on an IP-ring $\mathcal{F}^{(1)}$ comes from the fact that in our proof we strongly use Theorem 4.3 and its consequence stated in (4.1). In fact, the theorem works for any IP-ring $\mathcal{F}^{(1)}$ such that condition (4.1) holds.

By Theorem 4.11 with $\mathcal{Y}$ trivial, one obtains the following result immediately.

Corollary 4.13. *Let $(X,\mathcal{X},\mu,T)$ be a system and $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ be an* IP-*set. Then there exists an* IP-*ring $\mathcal{F}^{(1)}$ of $\mathcal{F}$ such that for any* IP-*ring $\mathcal{F}^{(2)}\subseteq\mathcal{F}^{(1)}$ there exists an $\mathcal{F}$-monotone subset $A\subseteq\{n_\alpha\}_{\alpha\in\mathcal{F}^{(2)}}$ such that*

$$h_\mu^A(T,\xi)=H_\mu(\xi\,|\,\mathcal{K}_F(X)) \tag{4.11}$$

for all measurable partitions ξ of X with $H_\mu(\xi)<\infty$, where $F=\{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$.

In particular, for any IP-*set $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ there exists an* IP-*ring $\mathcal{F}^{(1)}$ of $\mathcal{F}$ such that*

$$\max\{h_\mu^A(T,\xi):A\subseteq F \text{ is } \mathcal{F}\text{-monotone}\}=H_\mu(\xi\,|\,\mathcal{K}_F(X)), \tag{4.12}$$

where $F=\{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$.

Theorem 4.11 will follow directly from the following four lemmas.

Lemma 4.14. *Let $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ be an* IP-*set. Then there exists an* IP-*ring $\mathcal{F}^{(1)}$ of $\mathcal{F}$ such that for any* IP-*ring $\mathcal{F}^{(2)}\subseteq\mathcal{F}^{(1)}$ there exists an $\mathcal{F}$-monotone subset $A\subseteq\{n_\alpha\}_{\alpha\in\mathcal{F}^{(2)}}$ such that*

$$h_\mu^A(T,\xi\,|\,\mathcal{Y})\ge H_\mu(\xi\,|\,\mathcal{K}_F(X\,|\,Y))$$

for all measurable partitions ξ of X with $H_\mu(\xi\,|\,\mathcal{Y})<\infty$, where $F=\{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$.

Proof. The proof is similar to that of Lemma 3.6. We only point out the differences.

Let $\mathcal{F}^{(1)}$ be the IP-ring such that (4.1) holds. Consider $\mathcal{K}_F=\mathcal{K}_F(X\,|\,Y)$ to be the σ-algebra associated to $F=\{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$. All the results in the last subsection hold for this factor.

Let $\mathcal{G}_F$ be the family generated by $\{\{n_\alpha\}_{\alpha\in\mathcal{F}^{(2)}}:\mathcal{F}^{(2)}$ is an IP-ring of $\mathcal{F}^{(1)}\}$, that is, the family of all IP-subsets of F. Then by Hindman's Theorem $\mathcal{G}_F^*$ is a filter.

Claim. *For any measurable finite partitions ξ and η of X and $\varepsilon>0$, there exists a sequence $S\in\mathcal{G}_F^*$ such that for any $m\in S$,*

$$\int_Y H_y(T^{-m}\xi\,|\,\eta)\,d\nu(y)\ge H_\mu(\xi\,|\,\mathcal{K}_F)-\varepsilon. \tag{4.13}$$

Proof of Claim. It is easy to verify that $\mathcal{G}_F^*=\{S\subseteq\mathbb{Z}_+:$ there exists $\alpha_0\in\mathcal{F}^{(1)}$ such that $n_\alpha\in S$ for any $\alpha\in\mathcal{F}^{(1)}$ with $\alpha>\alpha_0\}$. For any $A,B\in\mathcal{X}$, since $1_A-\mathbb{E}(1_A\,|\,\mathcal{K}_F)\in L^2(X,\mathcal{K}_F,\mu)^\perp$, from Theorem 4.7 one deduces

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}}\int_Y\Big|\int_X T_\alpha(1_A-\mathbb{E}(1_A\,|\,\mathcal{K}_F))\cdot 1_B\,d\mu_y\Big|\,d\nu=0.$$

Equivalently,

$$\mathcal{G}_F^*\text{-}\lim\int_Y\Big|\int_X T^n(1_A-\mathbb{E}(1_A\,|\,\mathcal{K}_F))\cdot 1_B\,d\mu_y\Big|\,d\nu=0.$$

Let $\xi = \{A_1,\dots,A_k\}$ and $\eta = \{B_1,\dots,B_l\}$. Since $\mathcal{G}_F^*$ is a filter, for any fixed $\delta_1,\delta_2>0$ there exists $S\in\mathcal{G}_F^*$ such that for any $m\in S$ there is a set $E_m\in\mathcal{Y}$ with $\nu(E_m)>1-\delta_1$ satisfying

$$\Big|\mu_y(T^{-m}A_i\cap B_j)-\int_X T^m\mathbb{E}(1_{A_i}\,|\,\mathcal{K}_F)1_{B_j}\,d\mu_y\Big|<\delta_2 \tag{4.14}$$

for all $1\le i\le k, 1\le j\le l$ and $y\in E_m$. One concludes as in the proof of the Claim in the proof of Lemma 3.6.

For any IP-ring $\mathcal{F}^{(2)}\subseteq\mathcal{F}^{(1)}$, $S=\{n_\alpha\}_{\alpha\in\mathcal{F}^{(2)}}$ is an IP-set and hence $S\in\mathcal{G}_F$. Thus one can complete the proof in much the same way as the proof of Lemma 3.6. We omit the details. ∎

The following lemma is well known (see for example Lemma 4.15 in [W1]).

Lemma 4.15. *Let $r\ge 1$ be a fixed integer. For each $\epsilon>0$ there exists $\delta>0$ such that if $\xi=\{A_1,\dots,A_r\}$ and $\eta=\{C_1,\dots,C_r\}$ are two measurable partitions of X with $\sum_{i=1}^r\mu(A_i\triangle C_i)<\delta$ then the Rokhlin metric satisfies*

$$\rho_\mu(\xi,\eta)=H_\mu(\xi\,|\,\eta)+H_\mu(\eta\,|\,\xi)<\epsilon.$$

Lemma 4.16. *Let $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ be an* IP*-set and $B\in\mathcal{X}$. Then there exists an* IP*-ring $\mathcal{F}^{(1)}$ of $\mathcal{F}$ such that $B\in\mathcal{K}_F(X\,|\,Y)$ if and only if*

$$h_\mu^A(T,\{B,B^c\}\,|\,\mathcal{Y})=0$$

for all $\mathcal{F}$-monotone subsets $A\subseteq F$, where $F=\{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$.

Proof. Let $\mathcal{F}^{(1)}$ be the IP-ring such that (4.1) holds. Assume $B\in\mathcal{K}_F(X\,|\,Y)$. Let $A=\{n_{\beta_i}\}_{i\in\mathbb{N}}$ be an $\mathcal{F}$-monotone subset of $F=\{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$ and $\xi=\{B,B^c\}$.

Observe that $\|T^n1_B-T^m1_B\|_y^2=\mu_y(T^{-n}B\triangle T^{-m}B)$. Since $1_B\in L^2(X,\mathcal{K}_F(X\,|\,Y),\mu)$, by Corollary 4.10 there is $M\in\mathbb{N}$ such that for any $n>M$ there exists $E_n\in\mathcal{Y}$ with $\nu(E_n)<\delta$ satisfying, for any $y\notin E_n$,

$$\inf_{1\le j\le n-1}\|T_{\beta_n}1_B-T_{\beta_j}1_B\|_y<\delta,$$

where δ is chosen, as in Lemma 4.15, so small that $\rho_y(\xi,\eta):=\rho_{\mu_y}(\xi,\eta)<\varepsilon$ for $r=2$.

Hence for any $n>M$ there is $1\le j(n)\le n-1$ such that $\rho_y(T_{\beta_n}^{-1}\xi,T_{\beta_{j(n)}}^{-1}\xi)<\varepsilon$. So

$$H_y\Big(T_{\beta_n}^{-1}\xi\,\Big|\,\bigvee_{i=1}^{n-1}T_{\beta_i}^{-1}\xi\Big)\le H_y(T_{\beta_n}^{-1}\xi\,|\,T_{\beta_{j(n)}}^{-1}\xi)\le\rho_y(T_{\beta_n}^{-1}\xi,T_{\beta_{j(n)}}^{-1}\xi)<\varepsilon.$$

For any $y \in Y$, $H_y(T_{\beta_n}^{-1}\xi | T_{\beta_j}^{-1}\xi) \le \log 2$. Therefore

$$\begin{aligned} h_\mu^A(T,\xi \mid \mathcal{Y}) &= \limsup_{n\to\infty} \frac{1}{n} \int_Y H_y\Big(\bigvee_{i=1}^{n} T_{\beta_i}^{-1}\xi\Big)\, d\nu(y) \\ &= \limsup_{n\to\infty} \frac{1}{n} \int_Y \sum_{i=2}^{n} H_y\Big(T_{\beta_i}^{-1}\xi \,\Big|\, \bigvee_{j=1}^{i-1} T_{\beta_j}^{-1}\xi\Big)\, d\nu(y) \\ &= \limsup_{n\to\infty} \frac{1}{n} \Big(\int_{E_n} \sum_{i=2}^{n} H_y\Big(T_{\beta_i}^{-1}\xi \,\Big|\, \bigvee_{j=1}^{i-1} T_{\beta_j}^{-1}\xi\Big)\, d\nu(y) \\ &\qquad + \int_{Y\setminus E_n} \sum_{i=2}^{n} H_y\Big(T_{\beta_i}^{-1}\xi \,\Big|\, \bigvee_{j=1}^{i-1} T_{\beta_j}^{-1}\xi\Big)\, d\nu(y)\Big) \\ &\le \delta \log 2 + \varepsilon. \end{aligned}$$

Since ε and δ are arbitrary, it follows that $h_\mu^A(T,\xi \mid \mathcal{Y}) = 0$.

Now we show the converse. If $B \notin \mathcal{K}_F(X \mid Y)$ then $H_\mu(\{B,B^c\} \mid \mathcal{K}_F(X \mid Y)) > 0$. So by Lemma 4.14 there exists an $\mathcal{F}$-monotone subset A of F such that

$$h_\mu^A(T,\{B,B^c\} \mid \mathcal{Y}) \ge H_\mu(\{B,B^c\} \mid \mathcal{K}_F(X \mid Y)) > 0. \ ■$$

LEMMA 4.17. *Let $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ be an* IP*-set. Then there exists an* IP*-ring $\mathcal{F}^{(1)}$ of $\mathcal{F}$ such that for any finite measurable partition ξ of X and any $\mathcal{F}$-monotone subset $A \subseteq F$,*

$$h_\mu^A(T,\xi \mid \mathcal{Y}) \le H_\mu(\xi \mid \mathcal{K}_F(X \mid Y)), \tag{4.15}$$

where $F = \{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$.

Proof. Let $\mathcal{F}^{(1)}$ be the IP-ring such that (4.1) holds. In the proof of Lemma 3.8, replace $\mathcal{K}(X \mid Y)$ by $\mathcal{K}_F(X \mid Y)$ and use Lemma 4.16. ■

4.4. *Rigid and mildly mixing extensions.* Let $(X,\mathcal{X},\mu,T)$ be a system and $(Y,\mathcal{Y},\nu,T)$ one of its factors.

DEFINITION 4.18 ([FK]). Let $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ be an IP-set and $\mathcal{F}^{(1)}$ an IP-ring. The system $(X,\mathcal{X},\mu,T)$ is *$\mathcal{Y}$-mixing along $\mathcal{F}^{(1)}$* if for each $f,g \in L^2(X\times X, \mathcal{X}\otimes\mathcal{X}, \mu\times_Y \mu)$,

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \Big\{ \int_{X\times X} g\cdot(T\times T)_\alpha f\, d\mu\times_Y\mu - \int_Y \mathbb{E}(g \mid \mathcal{Y})\cdot(T\times T)_\alpha \mathbb{E}(f \mid \mathcal{Y})\, d\nu \Big\} = 0. \tag{4.16}$$

REMARK 4.19. It is easy to prove [Z2, Theorem 2.5.] that $(X,\mathcal{X},\mu,T)$ is $\mathcal{Y}$-mixing along $\mathcal{F}^{(1)}$ if and only if for each $f,g \in L^2(X,\mathcal{X},\mu)$,

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}} \int_X |\mathbb{E}(gT_\alpha f \mid \mathcal{Y}) - \mathbb{E}(g \mid \mathcal{Y}) T_\alpha \mathbb{E}(f \mid \mathcal{Y})|\, d\mu = 0.$$

PROPOSITION 4.20. *Let $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ be an* IP*-set and $\mathcal{F}^{(1)}$ an* IP*-ring as in* (4.1)*. Then the following conditions are equivalent*:

(1) *$(X,\mathcal{X},\mu,T)$ is $\mathcal{Y}$-mixing along $\mathcal{F}^{(1)}$.*
(2) *For any $f\in L^2(X,\mathcal{Y},\mu)^\perp$ and $g\in L^2(X,\mathcal{X},\mu)$,*

$$\text{IP-}\lim_{\alpha\in\mathcal{F}^{(1)}}\int_Y |\mathbb{E}(gT_\alpha f\,|\,\mathcal{Y})|\,d\nu=0.$$

(3) *$\mathcal{K}_F(X\,|\,Y)=\mathcal{Y}$, where $F=\{n_\alpha\}_{\alpha\in\mathcal{F}^{(1)}}$.*

Proof. This follows from Theorem 4.7. ∎

DEFINITION 4.21.

(1) $(X,\mathcal{X},\mu,T)$ is a *rigid extension over $\mathcal{Y}$* if there exists an IP-set F such that $\mathcal{X}=\mathcal{K}_F(X\,|\,Y)$.
(2) $(X,\mathcal{X},\mu,T)$ is a *mild mixing extension over $\mathcal{Y}$* if for any IP-set F, $\mathcal{K}_F(X\,|\,Y)=\mathcal{Y}$.

The following theorem follows easily from the work done in the previous subsection. We leave the proof to the reader.

THEOREM 4.22.

(1) *$(X,\mathcal{X},\mu,T)$ is a rigid extension over $\mathcal{Y}$ if and only if there exists an* IP*-set F such that $h_\mu^A(T\,|\,\mathcal{Y})=0$ for all $\mathcal{F}$-monotone subsets $A\subseteq F$.*
(2) *Let $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ be an* IP*-set and $\mathcal{F}^{(1)}$ as in* (4.1)*. Then $(X,\mathcal{X},\mu,T)$ is $\mathcal{Y}$-mixing along $\mathcal{F}^{(1)}$ if and only if for any* IP*-ring $\mathcal{F}^{(2)}\subseteq\mathcal{F}^{(1)}$ there exists an $\mathcal{F}$-monotone subset $A\subseteq\{n_\alpha\}_{\alpha\in\mathcal{F}^{(2)}}$ such that $h_\mu^A(T,\xi\,|\,\mathcal{Y})=H_\mu(\xi\,|\,\mathcal{Y})$ for all measurable partitions ξ with $H_\mu(\xi\,|\,\mathcal{Y})<\infty$.*
(3) *$(X,\mathcal{X},\mu,T)$ is a mild mixing extension over $\mathcal{Y}$ if and only if for any* IP*-set F there exists an $\mathcal{F}$-monotone subset $A\subseteq F$ such that $h_\mu^A(T,\xi\,|\,\mathcal{Y})=H_\mu(\xi\,|\,\mathcal{Y})$ for all measurable partitions ξ with $H_\mu(\xi\,|\,\mathcal{Y})<\infty$.*

REMARK 4.23. Parts (1) and (3) of Theorem 4.22 appear in [Z2], and the cases when $(Y,\mathcal{Y},\nu,T)$ is the trivial factor appear in [Z1], but stated in a slightly different language. Observe that the definitions of $\mathrm{AP}(\mathcal{Y},\{n_\alpha\},\mathcal{F}^{(1)})$ (Definition 4.4) and a rigid extension (Definition 4.21) differ from [Z2]. Also our method is different from that in [Z2].

5. An application. In this section we give an application of Theorems 3.4 and 4.11.

THEOREM 5.1. *Suppose that $(Y,\mathcal{Y},\nu,T)$ is a factor of the ergodic system $(X,\mathcal{X},\mu,T)$. Then*

$$\max_A\{h_\mu^A(T\,|\,\mathcal{Y})\}\in\{\log k:k\in\mathbb{N}\}\cup\{\infty\}.$$

Proof. Denote by $(K,\mathcal{K},\kappa,T)$ the factor of $(X,\mathcal{X},\mu,T)$ associated to the T-invariant σ-algebra $\mathcal{K}(X\,|\,Y)$. Since $(X,\mathcal{X},\mu,T)$ is ergodic, by the Rokhlin Theorem it is isomorphic to a skew-product over $(K,\mathcal{K},\kappa,T)$. Explicitly, there exists a probability space $(U,\mathcal{U},\rho)$, which may be a finite set with the uniform probability measure or the unit interval with the Lebesgue measure, and a measurable function γ from Y to the automorphisms of $(U,\mathcal{U},\rho)$ such that $(X,\mathcal{X},\mu,T)\cong(K\times U,\mathcal{K}\otimes\mathcal{U},\kappa\times\rho,T_\gamma)$, where $T_\gamma(x,u)=(Tx,\gamma(x)u)$.

If ξ_1 and ξ_2 are finite partitions of K and U respectively, define partitions ξ_1' and ξ_2' of $K\times U$ by $\xi_1'=\xi_1\times U=\{B\times U:B\in\xi_1\}$ and $\xi_2'=K\times\xi_2=\{K\times B:B\in\xi_2\}$. By Theorem 3.4 for any sequence $S\in\mathcal{D}^*$, there exists a subsequence $A\subseteq S$ such that

$$\begin{aligned}h^A_{\kappa\times\rho}(T_\gamma,\xi_1\times\xi_2\,|\,\mathcal{Y})&=H_{\kappa\times\rho}(\xi_1\times\xi_2\,|\,\mathcal{K})=H_{\kappa\times\rho}(\xi_1'\vee\xi_2'\,|\,\mathcal{K})\\&=H_{\kappa\times\rho}(\xi_2')=H_\rho(\xi_2).\end{aligned}$$

Thus, $h^A_\mu(T\,|\,\mathcal{Y})=\sup_{\xi_1,\xi_2}h^A_{\kappa\times\rho}(T_\gamma,\xi_1\times\xi_2\,|\,\mathcal{Y})$ is $\log k$ for some $k\in\mathbb{N}$ if U is a finite set, and ∞ if U is continuous. So

$$h^A_\mu(T\,|\,\mathcal{Y})\in\{\log k:k\in\mathbb{N}\}\cup\{\infty\}.$$

In particular, one gets the assertion. ∎

REMARK 5.2.

(1) One can use Theorem 4.11 instead of Theorem 3.4 to prove Theorem 5.1.

(2) In fact, what is proved in Theorem 5.1 is that for any sequence $S\in\mathcal{D}^*$, there exists a subsequence $A\subseteq S$ such that $h^A_\mu(T\,|\,\mathcal{Y})\in\{\log k:k\in\mathbb{N}\}\cup\{\infty\}$. Similarly, using Theorem 4.11 one can show that for any IP-set $\{n_\alpha\}_{\alpha\in\mathcal{F}}$ there exists an IP-ring $\mathcal{F}^{(1)}$ of $\mathcal{F}$ such that for any IP-ring $\mathcal{F}^{(2)}\subseteq\mathcal{F}^{(1)}$ there exists an $\mathcal{F}$-monotone subset $A\subseteq\{n_\alpha\}_{\alpha\in\mathcal{F}^{(2)}}$ such that $h^A_\mu(T\,|\,\mathcal{Y})\in\{\log k:k\in\mathbb{N}\}\cup\{\infty\}$.

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