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Published in:
Journal fuer die Reine und Angewandte Mathematik

DOI:
10.1515/crelle-2014-0005

Publication date:
2016

Document version
Peer reviewed version

Document license:
Unspecified

Citation for published version (APA):
Ultraproducts, QWEP von Neumann Algebras, and the Effros-Maréchal Topology

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May 13, 2013

Abstract

Based on the analysis on the Ocneanu/Groh-Raynaud ultraproducts and the Effros-Maréchal topology on the space $\mathcal{vN}(H)$ of von Neumann algebras acting on a separable Hilbert space $H$, we show that for a von Neumann algebra $M \in \mathcal{vN}(H)$, the following conditions are equivalent:

(1) $M$ has the Kirchberg’s quotient weak expectation property (QWEP).

(2) $M$ is in the closure of the set $\mathcal{F}_{\text{inj}}$ of injective factors on $H$ with respect to the Effros-Maréchal topology.

(3) $M$ admits an embedding $i$ into the Ocneanu ultrapower $R_{\omega}$ of the injective $\text{III}_{1}$ factor with a normal faithful conditional expectation $\pi: R_{\omega} \to i(M)$.

(4) For every $\varepsilon > 0$, $n \in \mathbb{N}$ and $\xi_1, \ldots, \xi_n \in F_M$, there is $k \in \mathbb{N}$ and $a_1, \ldots, a_n \in M_k(C)$, such that $|\langle \xi_i, \xi_j \rangle - \text{tr}_k(a_i a_j)| < \varepsilon$ ($1 \leq i, j \leq n$), where $\text{tr}_k$ is the tracial state on $M_k(C)$, and $P^i_M$ is the natural cone in the standard form of $M$.

1 Introduction

In the seminal paper [Kir93], Kirchberg revealed the unexpected connection among tensor products of $C^*$-algebras, the weak expectation property (WEP) of Lance [La73], and the Connes’s embedding problem type $\text{III}_1$ factors. A $C^*$-algebra is said to have WEP, if for any faithful representation $A \subset B(H)$, there is a unital completely positive (ucp) map $\Phi: B(H) \to A^{**}$ such that $\Phi|_A = \text{id}_A$.

A $C^*$-algebra $A$ is said to have the quotient weak expectation property (QWEP) if there is a surjective *-homomorphism from a $C^*$-algebra $B$ with WEP onto $A$. Among other interesting results, Kirchberg proved that the following conditions are equivalent:

(1) $C^*(F_\infty) \otimes_{\text{min}} C^*(F_\infty) = C^*(F_\infty) \otimes_{\text{max}} C^*(F_\infty)$.

(2) Every $C^*$-algebra has QWEP.

(3) Every $\text{III}_1$ factor $N$ with separable predual embeds into the tracial ultrapower $R^\omega$ (for some $\omega \in \beta\mathbb{N} \setminus \mathbb{N}$) of the hyperfinite $\text{III}_1$ factor $R$.

(2) is now called Kirchberg’s QWEP conjecture, and (3) is called the Connes’s embedding conjecture. It was mentioned for the first time in [Kir93]. See also the excellent survey [Oz04] on the QWEP conjecture. Nowadays many interesting equivalent conditions of the above conjectures are known. On the other hand,
the QWEP conjecture also has another connection to the topological properties of the space of von Neumann algebras. The Effros-Maréchal topology on the space $vN(H)$ of von Neumann algebras acting on a fixed Hilbert space $H$ is the weakest topology on $vN(H)$ for which the map

$$N \mapsto \|\varphi|_N\|$$

is continuous for every $\varphi \in \mathcal{B}(H)_\sigma$. Based on the work of Effros [Eff65-1, Eff65-2] on the Borel structure of $vN(H)$, this topology was defined by Maréchal in [Mar73] so that it generates the Effros Borel structure. Later it was intensively studied in [HW98, HW00], where the second and third-named authors showed that this topology was indeed well-matched with Tomita-Takesaki theory and could be used as a tool for the study of global properties of von Neumann algebras. Among other things, it was proved [HW00, Theorem 5.8] that when $H$ is separable, a $\text{II}_1$ factor $N \in vN(H)$ is in the closure of the set $F_{\text{inj}}$ of injective factors on $H$, if and only if $N$ embeds into $R^\omega$. Consequently, Connes’s embedding conjecture (hence all conditions (1)-(3) above) is equivalent to

(4) $F_{\text{inj}}$ is dense in $vN(H)$.

In this paper, we establish further connection among ultraproducts, the approximation by injective factors, and QWEP von Neumann algebras. To this we make use of the recent work of the first and the second-named authors on the ultraproducts of general von Neumann algebras [AH12]. We also carry on the analysis of the natural cone in the standard form [Haa75]. The main result of the paper is as follows. Let $R_\infty$ (resp. $R_\lambda$) denote the injective factor of type $\text{III}_1$ (resp. type $\text{III}_\lambda$ ($0 < \lambda < 1$)). We assume $H$ is separable infinite-dimensional.

**Theorem 1.1.** Let $0 < \lambda < 1$ and let $M \in vN(H)$, and let $P^\lambda_M$ be the natural cone in the standard form of $M$. The following conditions are equivalent.

1. $M$ has QWEP.
2. $M \in F_{\text{inj}}$.
3. There is an embedding $i: M \rightarrow R^\omega_\infty$ and a normal faithful conditional expectation $\varepsilon: R^\omega_\infty \rightarrow i(M)$.
4. There is an embedding $i: M \rightarrow R^\omega_\lambda$ and a normal faithful conditional expectation $\varepsilon: R^\omega_\lambda \rightarrow i(M)$.
5. There is $\{k_n\}_{n=1}^\infty \subset N$ and a normal faithful state $\varphi_n$ on $M_{k_n}(\mathbb{C})$ ($n \in \mathbb{N}$), an embedding $i: M \rightarrow (M_{k_n}(\mathbb{C}), \varphi_n)^\omega$ and a normal faithful expectation $\varepsilon: (M_{k_n}(\mathbb{C}), \varphi_n)^\omega \rightarrow i(M)$.
6. For every $\varepsilon > 0, n \in \mathbb{N}$ and $\xi_1, \cdots, \xi_n \in P^\lambda_M$, there exist $k \in \mathbb{N}$ and $a_1, \cdots, a_n \in M_k(\mathbb{C})_+$ such that

$$|\langle \xi_i, \xi_j \rangle - \text{tr}_k(a_ia_j)| < \varepsilon \quad (1 \leq i, j \leq n).$$

Here, $(N_n, \varphi_n)^\omega$ denotes the Ocneanu ultraproduct of $\{N_n\}_{n=1}^\infty$ with respect to the sequence of normal faithful states $\{\varphi_n\}_{n=1}^\infty$ (see §2).

The organization of the paper is as follows. In §2 we recall necessary backgrounds about ultraproducts, Effros-Maréchal topology. In §3, we prove the
relation between embedding into the Ocneanu ultraproduct and the limit in the
Effros-Maréchal topology. Using this, we prove the equivalence of (1)-(5) in the
above theorem. In §4, we prove the equivalence of (6) and (1) in the above
theorem.

2 Preliminaries

2.1 Notation

Throughout the paper, \(\omega \in \beta \mathbb{N} \setminus \mathbb{N}\) denotes a fixed free ultrafilter on \(\mathbb{N}\). \(H\)
denotes a separable Hilbert space and \(vN(H)\) the space of all von Neumann
algebras acting on \(H\) (we assumed all von Neumann algebras contain \(1 = \text{id}_H\)).
Let \(M\) be a von Neumann algebra, \(\varphi\) be a normal state on \(M\). As usual, we
define two norms \(\| \cdot \|_\varphi, \| \cdot \|_{\varphi}^{\#}\) by
\[
\|x\|_\varphi := \varphi(x^*x)^{1/2}, \quad \|x\|_{\varphi}^{\#} := \varphi(x^*x + xx^*)^{1/2}, \quad x \in M.
\]
For a sequence \((M_n)_{n}\) of von Neumann algebras, \(\ell^\infty(\mathbb{N}, M_n)\) is the \(C^*\)-algebra
of all norm-bounded sequences \((x_n)_{n} \in \prod_{n \in \mathbb{N}} M_n\).

2.2 Natural cone \(\mathcal{P}_M^\natural\)

Recall the following \[Haa75\]:

Definition 2.1. Let \((M, H, J, \mathcal{P}_M^\natural)\) be a quadruple, where \(M\) is a von Neumann
algebra, \(H\) is a Hilbert space on which \(M\) acts, \(J\) is an antilinear isometry on \(H\) with
\(J^2 = 1\), and \(\mathcal{P}_M^\natural \subset H\) is a closed convex cone which is self-dual, i.e.,
\(\mathcal{P}_M^\natural = (\mathcal{P}_M^\natural)^0\), where
\[
(\mathcal{P}_M^\natural)^0 := \{\xi \in H; \langle \xi, \eta \rangle \geq 0, \eta \in \mathcal{P}_M^\natural\}.
\]
Then \((M, H, J, \mathcal{P}_M^\natural)\) is called a standard form if the following conditions are satisfied:

1. \(JM J = M'\).
2. \(J\xi = \xi, \xi \in \mathcal{P}_M^\natural\).
3. \(x J x (\mathcal{P}_M^\natural) \subset \mathcal{P}_M^\natural, x \in M\).
4. \(J x J = x^*, x \in Z(M)\).

We remark that condition 4. automatically follows from the other three
conditions \[AH12, Lemma 3.19\]. The existence and the uniqueness of the standard
form was established in \[Haa75\]. \(\mathcal{P}_M^\natural\) is called the natural cone of \(M\).

It was independently introduced by Connes \[Con72\] and Araki \[Ara74\], and if \(M\) is \(\sigma\)-finite with a normal faithful state \(\varphi\), then on the GNS Hilbert space
\(H = L^2(M, \varphi)\), \(\mathcal{P}_M^\natural\) is realized as
\[
\mathcal{P}_M^\natural = \{a J_\varphi a J_\varphi \xi_\varphi; a \in M\} = \{\Delta_\varphi^{1/2} a \xi_\varphi, a \in M_+\}.
\]
Here, $\Delta_{\varphi}$ (resp. $J_{\varphi}$) is the modular (resp. modular conjugation) operator of $\varphi$. $\mathcal{P}_M$ induces an order structure on $H$ by

$$\xi \leq \eta \Leftrightarrow \xi - \eta \in \mathcal{P}_M^2.$$  

This order structure was intensively studied in [Con74, Ara74]. Among others, it holds that [Ara74] every positive $\varphi \in M_+$ is represented as $\varphi = \omega_{\xi_{\varphi}}$ by a unique vector $\xi_{\varphi} \in \mathcal{P}_M^2$ and we have the Araki-Powers-Størmer inequality:

$$\|\xi_{\varphi} - \xi_{\psi}\|^2 \leq \|\varphi - \psi\| \leq \|\xi_{\varphi} - \xi_{\psi}\|\|\xi_{\varphi} + \xi_{\psi}\|.$$  

The readers are referred to these papers for more detailed information on the natural cone.

### 2.3 The Ocneanu and the Groth-Raynaud Ultraproduct

Let $(M_n, \varphi_n)_n$ be a sequence of pairs of σ-finite von Neumann algebras equipped with normal faithful states. Let $\mathcal{L}_\omega := \mathcal{L}_\omega \cap \mathcal{L}_\omega$, where

$$\mathcal{L}_\omega = \mathcal{L}_\omega(M_n, \varphi_n) := \{(x_n)_n \in \ell^\infty(N, M_n); \|x_n\|_{\varphi_n} \to 0\},$$

and let $\mathcal{M}_\omega$ be the multiplier algebra of $\mathcal{L}_\omega$. The **Ocneanu ultraproduct** $(M_n, \varphi_n)^\omega$ of $(M_n, \varphi_n)_n$ is the quotient algebra $\mathcal{M}_\omega/\mathcal{L}_\omega$. For each $n \in N$, let $H_n = L^2(M_n, \varphi_n)$ be the GNS Hilbert space of $(M_n, \varphi_n)$, and let $H_\omega$ be the ultraproduct of $(H_n)_n$. Define a $^*$-representation $\pi_\omega : \ell^\infty(N, M_n) \to \mathcal{B}(H_\omega)$ by

$$\pi_\omega((x_n)_n)(\xi_\omega) := (x_n \xi_n)_\omega, \quad (x_n)_n \in \ell^\infty(N, M_n), \ (\xi_\omega)_\omega \in H_\omega.$$  

The **Groth-Raynaud ultraproduct** $\prod^\omega M_n$ is the von Neumann algebra $\pi_\omega(\ell^\infty(N, M_n))''$ acting on $H_\omega$. Let $\xi_\omega \in H_\omega$ be the cyclic vector corresponding to $\varphi_n$, and let $\mathcal{L}_\omega = (\xi_\omega)_\omega \in H_\omega$. Let $p \in \prod^\omega M_n$ be the support projection of the normal state $(\cdot, \xi_\omega, \xi_\omega)$ on $\prod^\omega M_n$. Then by [AH12, Proposition 3.15], $(M_n, \varphi_n)^\omega \cong p(\prod^\omega M_n)p$. For more details about ultraproducts, see [AH12].

### 2.4 Effros-Maréchal Topology on vN($H$)

As explained in the introduction, the **Effros-Maréchal topology** is the weakest topology on $\text{vN}(H)$ which makes each functional $\text{vN}(H) \ni N \mapsto \|\varphi|N\|$ continuous ($\varphi \in \mathcal{B}(H)_+$). As $H$ is separable, this makes $\text{vN}(H)$ a Polish space, and the topology can be described by the concepts of limsup and liminf of a sequence in $\text{vN}(H)$ (the limsup presented here is a refinement [HW98] of s-limsup given in [Tuk85]). Since we only consider the case where $H$ is separable, we use the following simplified equivalent definitions (see [HW98, §2] for the original definition).

**Definition 2.2.** Let $(M_n)_n \subset \text{vN}(H)$.

1. $\liminf_{n \to \infty} M_n$ is the set of all $x \in \mathcal{B}(H)$ for which there exists $(x_n)_n \in \ell^\infty(N, M_n)$ that converges to $x$ $^*$-strongly.

2. $\limsup_{n \to \infty} M_n$ is the von Neumann algebra generated by the set of all $x \in \mathcal{B}(H)$ for which there exists $(x_n)_n \in \ell^\infty(N, M_n)$ such that $x$ is a weak-limit point of $(x_n)_{n=1}^\infty$. 

4
It is proved in [HW98, Theorems 2.8, 3.5] that for a sequence \( \{M_n\}_{n=1}^{\infty} \subset vN(H) \) and \( M \in vN(H) \),
\[
\lim_{n \to \infty} M_n = M \text{ in } vN(H) \iff \lim \inf_{n \to \infty} M_n = \lim \sup_{n \to \infty} M_n, \\
\left( \lim \sup_{n \to \infty} M_n \right)' = \lim \inf_{n \to \infty} M_n'.
\]

We will also make use of the ultralimit version of the above concepts.

**Definition 2.3.** Let \( (M_n)_{n \in \mathbb{N}} \subset vN(H) \). We define

1. \( \lim \inf_{n \to \omega} M_n \) is the set of all \( x \in B(H) \) for which there exists \( (x_n)_{n \in \mathbb{N}} \in \ell^\infty(\mathbb{N}, M_n) \) such that \( x = \text{so}^*- \lim_{n \to \omega} x_n \).

2. \( \lim \sup_{n \to \omega} M_n \) is the von Neumann algebra generated by the set of all \( x \in B(H) \) for which there exists \( (x_n)_{n \in \mathbb{N}} \in \ell^\infty(\mathbb{N}, M_n) \) such that \( x = \text{wo} - \lim_{n \to \omega} x_n \).

Again they are different from the original definitions. It also holds that

\[
M = \lim_{n \to \omega} M_n \text{ in } vN(H) \iff \lim \inf_{n \to \omega} M_n = M = \lim \sup_{n \to \omega} M_n, \\
\left( \lim \sup_{n \to \omega} M_n \right)' = \lim \inf_{n \to \omega} M_n'.
\]

Finally, we will consider the following subsets of \( vN(H) \) (see the introduction of [HW00] for more details):

- \( F \), the set of factors acting on \( H \).
- \( F_X \), the set of factors of type \( X \) acting on \( H \), where \( X \) runs among the standard numberings of the types of factors, such as \( \Pi_1 \) or \( \Pi_\lambda \).
- \( F_{\text{inj}} \), the set of injective factors acting on \( H \).
- \( F^{\text{st}} \), the set of factors acting standardly on \( H \).
- \( \text{SA}(M) \) the set of von Neumann subalgebras of \( M \in vN(H) \).

For a fixed normal faithful state \( \varphi \) on \( M \), we denote \( \text{SA}_{\varphi}(M) \) to be the set of those \( N \in \text{SA}(M) \) satisfying \( \sigma_t^\varphi(N) = N \ (t \in \mathbb{R}) \) (see [HW98, §2]). We also make use of self-explanatory extensions of the above notation, such as \( F_{\text{inj}}^{\text{st}} = F_{\text{inj}} \cap F^{\text{st}} \).

### 3 Embedding into the Ocneanu Ultraproducts and Effros-Maréchal Topology

In this section, we consider a separable infinite-dimensional Hilbert space \( H \). An *embedding* is understood to be a unital normal injective *-homomorphism of one von Neumann algebra into another. The main technical part of this section deals with versions of the following statements about von Neumann algebras \( M, N \in vN(H) \):
1. There is a sequence \((\psi_n)_n \subset S_{\text{ad}}(M)\), an embedding of \(i: N \to (M, \psi_n)^\omega\) and a faithful normal conditional expectation \(\varepsilon\) of \((M, \psi_n)^\omega\) onto \(i(N)\);

2. There is a separable Hilbert space \(K\), a sequence of isomorphic copies \(M_n \in vN(K)\) of \(M\) and an isomorphic copy \(N_0 \in vN(K)\) of \(N\) such that \(M_n \to N_0\) in the Effros-Maréchal topology;

We prove that 1. is equivalent to 2. (Theorem 3.1 and Theorem 3.3) As an application we give a new characterization of the closure of the set of injective factors in \(vN(H)\) (see [HW00, §4-5] for more details).

### 3.1 Approximation Theorem and The Closure of Injective Factors.

We begin by the following

**Theorem 3.1.** Let \(N \in vN(H)\). Assume we are given a sequence \((M_n) \subset vN(H)\) such that \(M_n \to N\) in \(vN(H)\). Fix \(\chi \in S_{\text{ad}}(B(H))\), and let \(\psi_n := \chi|_{M_n}\). Then there exists an embedding \(i \colon N \to (M_n, \psi_n)^\omega\) such that \(\varphi = (\psi_n)^\omega \circ i\), and a normal faithful conditional expectation \(\varepsilon\) of \((M_n, \psi_n)^\omega\) onto \(i(N)\) such that \((\psi_n)^\omega \circ \varepsilon = (\psi_n)^\omega\).

**Proof.** Let \(x \in N\). By [HW98, Theorem 2.8], \(N = \lim\inf_{n \to \infty} M_n\) and we may choose \((x_n)_n \in \ell^\infty(N, M_n)\) satisfying \(x_n \xrightarrow{\text{w.o.}} x\). It is clear that \((x_n)_n \in \mathcal{M}_\omega(M_n, \psi_n)\) because of the joint continuity of operator product in strong*-topology on bounded sets, and also that \((x_n)^\omega\) is independent of the choice of the sequence \((x_n)_n\) converging to \(x\). Hence we may define \(i \colon N \to (M_n, \psi_n)^\omega\) by \(i(x) = (x_n)^\omega\), which is clearly an injective \(*\)-homomorphism, and as

\[
(\psi_n)^\omega \circ i(x) = \lim_{n \to \omega} \psi_n(x_n) = \lim_{n \to \omega} \chi(x_n) = \varphi(x),
\]

we have \((\psi_n)^\omega \circ i = \varphi\). In particular, \(i\) is normal. Next, for \(y = (x_n)^\omega \in (M_n, \psi_n)^\omega\), let \(x := \lim\inf_{n \to \omega} x_n\). Then \(x \in \lim\sup_{n \to \infty} M_n = N\) by [HW98, Theorem 2.8]. We then define \(\varepsilon(y) := i(x)\). Let \(x \in N\) and suppose \(i(x) = (x_n)^\omega\) for \((x_n)_n \in \ell^\infty(N, M_n)\). Then as \(x_n \xrightarrow{\text{w.o.}} x\), we have \(\varepsilon \circ i(x) = \varepsilon((x_n)^\omega) = i(x)\), whence \(\varepsilon \circ i = i\). Therefore \(\varepsilon\) is a faithful conditional expectation of \((M_n, \psi_n)^\omega\) onto \(i(N)\). Next, let \((x_n)^\omega \in (M_n, \psi_n)^\omega\) and let \(x = \lim\inf_{n \to \omega} x_n\). Suppose \(i(x) = (x'_n)^\omega\), where \((x'_n)_n \in \ell^\infty(N, M_n)\). Then

\[
(\psi_n)^\omega \circ \varepsilon((x_n)^\omega) = (\psi_n)^\omega \circ i(x) = (\psi_n)^\omega((x'_n)^\omega)
= \lim_{n \to \omega} \psi_n(x'_n) = \lim_{n \to \omega} \chi(x'_n) = \chi(x)
= \lim_{n \to \omega} \chi(x_n) = (\psi_n)^\omega((x_n)^\omega),
\]

whence \((\psi_n)^\omega \circ \varepsilon = (\psi_n)^\omega\). Since \((\psi_n)^\omega\) is normal and faithful, \(\varepsilon\ is also normal. \)

**Corollary 3.2.** Let \(M, N \in vN(H)\), and assume \((M_n) \subset vN(H)\) has \(M_n \cong M(n \in \mathbb{N})\) and \(M_n \to N\). Then there exists a sequence \((\psi_n)_n \subset S_{\text{ad}}(M)\) and an embedding \(i\) of \(N\) into \((M, \psi_n)^\omega\), and a normal faithful conditional expectation of \((M, \psi_n)^\omega\) onto \(i(N)\).
Proof. Let $\varphi \in S_{\text{af}}(N)$. Using [HW98, Lemma 5.6], we find $\chi \in S_{\text{af}}(B(H))$ such that $\varphi = \chi|_{N}$. Let $\psi_n := \chi|_{M_n} \in S_{\text{af}}(M_n)$ for each $n \in \mathbb{N}$. For each $n \in \mathbb{N}$, take a $*$-isomorphism $\Phi_n : M \to M_n$ and let $\psi_n := \psi_n \circ \Phi_n$. Then $\Phi((x_n))^{\omega} = (\Phi_n(x_n))^{\omega}$ defines a $*$-isomorphism $\Phi : (M, \psi_n)^{\omega} \to (M_n, \psi_n^{\omega})$. By Theorem 3.1, there exists an embedding $i' : N \to (M_n, \psi_n^{\omega})$ and a normal faithful conditional expectation $\epsilon' : (M_n, \psi_n^{\omega}) \to i'(N)$. Then $i := \Phi^{-1} \circ i' : N \to (M, \psi_n^{\omega})$ and $\epsilon := \Phi^{-1} \circ \epsilon' \circ \Phi : (M, \psi_n^{\omega}) \to i(N)$ are the required embedding and the normal faithful conditional expectation. 

We now prove a partial converse to Theorem 3.1, which is at the same time a generalization of [HW00, Lemma 5.5] to the non-tracial case:

**Theorem 3.3.** Let $\{M_n\}_{n=1}^{\infty} \subset \nu \text{N}^{\omega}(H)$ and $N \in \nu \text{N}^{\omega}(H)$. Let $\psi_n \in S_{\text{af}}(M_n)$ $(n \in \mathbb{N})$. Assume that we are given an embedding $i : N \to (M_n, \psi_n)^{\omega}$ and a normal faithful conditional expectation $\epsilon : (M_n, \psi_n)^{\omega} \to i(N)$. Then there exists $(\nu_n) \subset \mathcal{U}(H)$ and a strictly increasing sequence $\{\nu_n\}_{n=1}^{\infty} \subset \mathbb{N}$ such that $\nu_n M_n u_{\nu_n}^{\omega} \to N$ in $\nu \text{N}(H)$.

**Proof.** For simplicity, we use notations $\tilde{M} = (M, \psi_n^{\omega})$ and $\tilde{\psi} = (\psi_n)^{\omega}$. Let $\tilde{\varphi} := \psi \circ \epsilon \in S_{\text{af}}(\tilde{M})$. Then by [AH12, Corollary 3.29], there exists $\varphi_n \in S_{\text{af}}(M_n)$ $(n \in \mathbb{N})$ such that $(M_n, \varphi_n)^{\omega} = \tilde{M}$ and $\varphi = (\varphi_n)^{\omega}$. Put $\varphi := \tilde{\varphi}|_{\iota(N)}$. Since each $M_n$ acts standardly on $H$, there exists a cyclic and separating vector $\xi_n \in H$ for $M_n$ such that $\varphi_n(x) = \langle x \xi_n, \xi_n \rangle (x \in M_n)$ for $n \in \mathbb{N}$. Let $\xi := (\xi_n)_{\omega} \in H_{\omega}$. Define as in [AH12, Theorem 3.7] an isometry $w : L^2(\tilde{M}, \tilde{\psi}) \to H_{\omega}$ given as the unique extension of $(x_n)^{\omega} \xi \varphi \to (x_n \xi_n)^{\omega}$ ($(x_n)^{\omega} \in \tilde{M}$). Let $K := w(L^2(\tilde{M}, \tilde{\psi}))$. Let $J_{\psi} : H \to H$ be the modular conjugation associated with the standard representation of $M_n$ on $H_n$. Let $J_{\omega} := (J_n)_{\omega} : H_{\omega} \to H_{\omega}$. Then by [AH12, Theorems 3.7 and 3.19], $J$ is the modular conjugation associated with the standard representation of $\prod \nu_n M_n$ on $H_{\omega}$, and $J_{\omega}|K = wJ_{\tilde{M}}w^*$. Here, $J_{\tilde{M}}$ is the modular conjugation associated with the standard representation of $M$ on $L^2(\tilde{M}, \tilde{\psi})$. Since $w(\tilde{M}) = i(N)$, $\varphi = \tilde{\varphi}|_{\iota(N)}$ and $\tilde{\psi} = \psi \circ \epsilon$ holds. Thus we may regard $L^2(i(N), \varphi)$ as a closed subspace of $L^2(\tilde{M}, \tilde{\psi})$ (thus $\xi_{\psi} = \xi_{\tilde{\psi}}$). In this case by the argument in [Tak72] $J_{i(N)} = J_{\tilde{M}}|L^2(i(N), \varphi)$ holds, where $J_{i(N)}$ is the modular conjugation associated with the natural representation $\pi_{\varphi}$ of $N$ on $L^2(i(N), \varphi)$ given by $\pi_{\varphi}(x)(y)\xi_{x} = i(xy)\xi_{x}$ $(x, y \in N)$. Put $L := w(L^2(i(N), \varphi)) \subset K \subset H_{\omega}$ and $w_0 := w|_{L^2(i(N), \varphi)}$. Let $P_L$ (resp. $P_K$) be the projection of $H_{\omega}$ onto $L$ (resp. $K$), and let $e_{L}$ be the projection of $K$ onto $L$. Let $e$ be the projection of $L^2(\tilde{M}, \tilde{\psi})$ onto $L^2(i(N), \varphi)$.

$$
\begin{array}{c}
L^2(\tilde{M}, \tilde{\psi}) \xrightarrow{w} K \xrightarrow{P_K} \subset H_{\omega} \\
\cup \quad e \quad \cup \quad e_{L} \\
L^2(i(N), \varphi) \xrightarrow{w_0} \subset L
\end{array}
$$

Since $\nu_n$ is separable, $L$ is a separable subspace of $H_{\omega}$. So by [HW00, Lemma 5.1], there exist unitaries $v_n \in \mathcal{U}(L, H)$ $(n \in \mathbb{N})$ such that $\xi = (v_n \xi_n)_{\omega}$ holds for every $\xi \in L$. Recall that to construct the Groth-Raynaud ultraproduct $\prod \nu_n M_n$, we used $\pi_{\varphi} : \ell^{\infty}(N, M_n) \to B(H_{\omega})$ given by $\pi_{\varphi}((x_n)_{\omega})(\xi_n)_{\omega} = (x_n \xi_n)_{\omega}$ for $(x_n)_{\omega} \in \ell^{\infty}(N, M_n)$ and $(\xi_n)_{\omega} \in H_{\omega}$. Note that the definition of $\pi_{\varphi}$ is
Then as elements of $\mathcal{B}(H_\omega)$, the following holds.

Claim 1. Let $(x_n)_n \in \ell^\infty(\mathbb{N}, M_n)$ and $(x'_n)_n \in \ell^\infty(\mathbb{N}, M'_n)$. Then as elements of $\mathcal{B}(H_\omega)$, the following holds.

$$\text{wo - lim}_{n \to \omega} v_n^* x_n v_n = P_L \pi_\omega((x_n)_n) P_L,$$

(1)

$$\text{wo - lim}_{n \to \omega} v_n^* x'_n v_n = P_L \pi_\omega((x'_n)_n) P_L.$$

(2)

Let $y := \text{wo - lim}_{n \to \omega} v_n^* x_n v_n$. Clearly $v_n^* x_n v_n \in P_L \mathcal{B}(H_\omega) P_L$, and for $\xi, \eta \in L$, we have

$$\langle y_\xi, \eta \rangle = \lim_{n \to \omega} \langle x_n v_n \xi, v_n \eta \rangle$$

$$= (\pi_\omega((x_n)_n)(v_n \xi), (v_n \eta)_{\omega})$$

$$= (\pi_\omega((x_n)_n) \xi, \eta),$$

whence (1) holds. (2) can be proved similarly.

Claim 2. The following holds:

$$P_L \pi_\omega(\ell^\infty(\mathbb{N}, M_n)) P_L \subset \pi_L(N),$$

(3)

$$P_L \pi_\omega(\ell^\infty(\mathbb{N}, M'_n)) P_L \subset \pi_L(N'),$$

(4)

where $\pi_L$ is the natural standard action of $N$ on $L$ unitarily equivalent to $\pi_\varphi$, i.e., $\pi_L(x) = w_0 \pi_\varphi(x) w_0^*$ ($x \in \mathbb{N}$). By [AH12, Theorem 3.7, Corollary 3.28], $P_K = w \omega^*, \omega^* (\prod^\infty M_n) w = M$ and $\rho: M \ni \pi_3(x) \mapsto w x \omega^* \in P_K(\prod^\infty M_n) P_K$ is a *-isomorphism. Note that by the existence of $\varepsilon: M \to i(\mathbb{N})$, $e$ satisfies $e \pi_3((x_n)_n)^e = \pi_\varphi(e \varepsilon((x_n)^e)) e = e \pi_3(e \varepsilon((x_n)^\omega))$ for $(x_n)^\omega \in \tilde{M}$. Now let $(x_n)_n \in \ell^\infty(\mathbb{N}, M_n)$. Then by [AH12, Corollary 3.16], there exists $(a_n)_n \in M^\omega(M_n, \varphi_n)$, $(b_n)_n \in L_\omega(M_n, \varphi_n)$ and $(e_n)_n \in L_\omega(M_n, \varphi_n)^*$ such that $x_n = a_n + b_n + e_n$ ($n \in \mathbb{N}$), and moreover

$$P_K \pi_\omega((x_n)_n) P_K = P_K(\pi_\omega((a_n)_n) P_K = w \pi_\varphi((a_n)^\omega) w^*.$$

Then as $P_L = e_L P_K$, it holds that

$$P_L \pi_\omega((x_n)_n) P_L = e_L P_K \pi_\omega((x_n)_n) P_K e_L$$

$$= e_L w \pi_\varphi((a_n)^\omega) w^* e_L$$

$$= w_0 e \pi_\varphi((a_n)^\omega) e w_0^*$$

$$= w_0 \pi_\varphi(e \varepsilon((a_n)^\omega)) e w_0^*$$

$$= \pi_L(i^{-1} \circ \varepsilon((a_n)^\omega)) \in \pi_L(N),$$

and (3) is proved. For (4), let $(x'_n)_n \in \ell^\infty(\mathbb{N}, M_n)$. Then $x'_n = J_n x_n J_n$, $x_n := J_n x'_n J_n \in M_n$ ($n \in \mathbb{N}$), and $\pi_\omega((x'_n)_n) = J_n \pi_\omega((x_n)_n) J_n$. Since $P_K = p J_n \rho J_\omega$, where $p = \text{supp}((\varphi_n)_\omega) \subseteq \prod^\infty M_n$, $P_K J_\omega = J_n P_K$ holds. Choose $(a_n)_n \in M^\omega(M_n, \varphi_n)$ as above so that $w \pi_\varphi((a_n)^\omega) w^* = P_K \pi_\omega((x_n)_n) P_K$ holds. Thus,
it holds that
\[ P_L \hat{\pi}_\omega((\epsilon_n'))P_L = \epsilon_L P_K J_{\omega} \pi_\omega((\epsilon_n'))J_{\omega} P_K \epsilon_L \]
\[ = \epsilon_L J_{\omega} P_K \pi_\omega((\epsilon_n'))P_K J_{\omega} \epsilon_L \]
\[ = J_L \epsilon_L w\pi_\omega((\epsilon_n'))w^* \epsilon_L J_L \]
\[ = J_L \pi_L (i^{-1} \circ \epsilon((\epsilon_n'))J_L \in \pi_L(N)', \]
and (4) is proved.

**Claim 3.** \( \lim_{n \to \omega} \epsilon_n^* M_n \epsilon_n = \pi_L(N) \).

To show the claim, by [HW00, Lemma 5.2], it suffices to show the following:

\[ \limsup_{n \to \omega} \epsilon_n^* M_n \epsilon_n \subset \pi_L(N), \quad (5) \]
\[ \limsup_{n \to \omega} \epsilon_n^* M_n' \epsilon_n \subset \pi_L(N)'. \quad (6) \]

To prove (5) and (6), it is enough to show that for every \( (\epsilon_n)_n \in \ell^\infty(N, M_n) \) and \( (\epsilon_n')_n \in \ell^\infty(N, M_n') \),

\[ \text{wo - lim} \ n \to \omega \ \epsilon_n^* \epsilon_n \epsilon_n \subset \pi_L(N), \]
\[ \text{wo - lim} \ n \to \omega \ \epsilon_n^* \epsilon_n \epsilon_n' \subset \pi_L(N)'. \]

But they are the consequences of Claim 1 and Claim 2.

Finally, as the representation \( \pi_L \) is standard and \( N \in \nu_N^H(H) \), there exists \( u \in U(H, H) \) such that \( u\pi_L(x)u^* = x \) \( (x \in N) \). Then by Claim 3, we have \( u_n M u_n^* \to N \) in \( \nu_N(H) \), where \( u_n = u \pi_n \in U(H) \). From this and the fact that \( \nu_N(H) \) is a separable metrizable space, we may find a subsequence \( \{ u_{n_k} \}_{k=1}^\infty \) so that \( u_{n_k} M u_{n_k}^* \to N \) \( (k \to \infty) \) in \( \nu_N(H) \).

In [HW00, Theorem 5.8], the second and the third-named authors proved that a type II_1 factor is in the closure of injective factors if and only if it embeds into \( R^\infty \), where \( R \) is the injective II_1 factor. Let \( R_\lambda^\infty \) (resp. \( R_\lambda \)) denote the injective factor of type III_\lambda (resp. type III_\lambda \( (0 < \lambda < 1) \)). As an application of the theorems above, we get the following result for general von Neumann algebras:

**Theorem 3.4.** Let \( N \in \nu_N(H) \) and \( 0 < \lambda < 1 \). Then the following are equivalent:

(i) \( N \in \mathcal{F}_{inj} \).

(ii) There is an embedding \( i: N \to R_\lambda^\infty \) and a normal faithful conditional expectation \( \varepsilon: R_\lambda^\infty \to i(N) \).

(iii) There is an embedding \( i: N \to R_\lambda^\infty \) and a normal faithful conditional expectation \( \varepsilon: R_\lambda^\infty \to i(N) \).

**Proof.** (i)\( \Rightarrow \) (ii): By [HW00, Theorem 2.10 (ii)], \( \mathcal{F}_{II_1} \cap \mathcal{F}_{inj} \) is dense in \( \mathcal{F}_{inj} \).

Therefore condition (i) implies that there exists a sequence \( (M_n)_n \) of injective type III_\lambda factors on \( H \) such that \( M_n \to N \). Then as \( M_n \cong R_\infty \) \( (n \in \mathbb{N}) \), by Corollary 3.2, there exists a sequence \( (\psi_n)_n \subset S_{\psi}(R_\infty) \) such that there exists
an embedding \( i : N \to (R_\infty, \psi_n)^{\omega} \) and a normal faithful conditional expectation \( \varepsilon : (R_\infty, \psi_n)^{\omega} \to i(N) \). By [AH12, Theorem 6.11], we have \( (R_\infty, \psi_n)^{\omega} \cong R_\infty^{\omega}. \)

Therefore (ii) holds. (ii)⇒(i): Let \( K_1, K_2 \) be Hilbert spaces such that \( \tilde{N} := N \tilde{\otimes} \mathbb{B}(K_1) \otimes C(K_2) \) acts standardly on \( H \otimes K, K := K_1 \otimes K_2 \). Then we obtain an embedding \( i' = i \otimes \text{id} : \tilde{N} \to Q^{\omega}, Q := R_\infty \mathbb{B}(K_1) \otimes C(K_2) \) and a normal faithful conditional expectation \( \varepsilon' = \varepsilon \otimes \text{id} : Q^{\omega} \to i'(N) \). Here we used the fact that \( Q^{\omega} \cong R_\infty \mathbb{B}(K_1) \otimes C(K_2) \) (cf. [MaTo12, Lemma 2.8]). Since \( Q, \tilde{N} \in vN^{\omega}(H \otimes K) \), by Theorem 3.3, there exist \( (\omega_n)_{n \in \mathbb{N}} \subset U(H \otimes K) \) such that \( \omega_n Q \omega_n \to \tilde{N} \) in \( vN(H \otimes K) \). In particular, as \( Q \cong R_\infty \), \( \tilde{N} \in F_{\infty} \) holds. Choose \( v_0 \in U(H \otimes K, H) \). Then by [HW00, Lemma 2.4], there exist \( (\omega_n)_{n \in \mathbb{N}} \subset U(H \otimes K) \) such that \( \omega_n v_n^* \tilde{N} v_n^* v_0^* \to N \) in \( vN(H) \). As \( v_0 \omega_n \tilde{N} v_n v_0^* \in F_{\infty} \), this shows that \( N \in F_{\infty} \) holds.

(i)⇒(iii) holds similarly.

\[ \square \]

**Remark 3.5.** Nou [Nou06] has shown that \( q \)-deformed Araki-Woods algebras (in the sense of Hiai [Hiai03], see also [Shl07]) have QWEP, whence by the above theorem they are embeddable into \( R_\infty^{\omega} \) within the range of a normal faithful conditional expectation.

The Effros-Maréchal topology gives an alternative proof of the following without logician’s method.

**Corollary 3.6** (Farah-Hart-Sherman [FHS11]). There exists a type II\(_1\) factor \( M \) with separable predual such that every type II\(_1\) factor \( N \) with separable predual admits an embedding \( i : N \to M^{\omega}. \)

**Proof.** Let \( \{M_n\}_{n=1}^{\infty} \) be a dense subset of \( F_{\Pi_1} \).

Define \( M := \bigotimes_{n \in \mathbb{N}} (M_n, \tau_n) \).

Then for every \( II_1 \) factor \( N \in vN(H) \), there exists a sequence \( \{n_k\}_{k=1}^{\infty} \) such that \( M_{n_k} \to N (k \to \infty) \). Then as in the proof of Theorem 3.1, there is an embedding \( i : N \to (M_{n_k}, \tau_{n_k})^{\omega} \) given by \( i(x) = (x_k)_{k=1}^{\infty} \), where \( (x_k)_{k=1}^{\infty} \in \ell^\infty(\mathbb{N}, \tau_{n_k}) \) is such that \( x_k \cong x \). Since each \( M_{n_k} \) embeds into the \( II_1 \) factor \( M \) in a trace-preserving way, \( (M_{n_k}, \tau_{n_k})^{\omega} \) embeds into the \( II_1 \) factor \( M^{\omega} \). Therefore \( N \) embeds into \( M^{\omega}. \)

Raynaud showed [Ray02, Proposition 1.14] that \( \prod^{\omega} \mathbb{B}(H) \) is not semifinite where \( H \) is infinite-dimensional and \( U \) is a free ultrafilter on the set \( I \) of all pairs \( (E, \varepsilon) \) where \( E \) is a finite-dimensional subspace of \( \mathbb{B}(H) \), and \( \varepsilon > 0 \) partially ordered by \( (E_1, \varepsilon_1) \leq (E_2, \varepsilon_2) \Leftrightarrow \varepsilon_1 \geq \varepsilon_2 \) and \( E_1 \subset E_2 \). The proof is based on [Ray02, Lemma 1.12, Lemma 1.13] that \( \mathbb{B}(H)^{**} \) is not semifinite, and by (local reflexivity) there is an embedding \( i : \mathbb{B}(H)^{**} \to \prod^{\omega} \mathbb{B}(H) \) and a normal faithful conditional expectation \( \varepsilon : \prod^{\omega} \mathbb{B}(H) \to i(\mathbb{B}(H))^{**} \). Therefore the large index set was required in his argument. We show that the same conclusion holds when \( I \) is replaced by \( \mathbb{N} \) using Effros-Maréchal topology.

**Corollary 3.7.** \( \prod^{\omega} \mathbb{B}(H) \) is not semifinite.

**Proof.** Let \( M \in vN(H) \) be an injective type III factor. Then by the proof of [HW00, Corollary 2.11], it is in the closure of the set \( F_{\infty} \) of type I\(_3\) factors on \( H \). Then by Theorem 3.1, there is a sequence \( \{\varphi_n\}_{n=1}^{\infty} \subset S_{\text{eff}}(\mathbb{B}(H)) \), an embedding \( i : M \to (\mathbb{B}(H), \varphi_n)^{\omega} \), and a normal faithful conditional expectation \( \varepsilon : (\mathbb{B}(H), \varphi_n)^{\omega} \to i(M) \). In particular, \( (\mathbb{B}(H), \varphi_n)^{\omega} \) is not semifinite by [Tom58,
Theorem 4.2. Let $H$ be a separable Hilbert space, and let $M \in \mathcal{vN}(H)$. The following conditions are equivalent.

1. $M \in \mathcal{F}_{\text{inj}}$.
2. $M$ has QWEP.

Proof. Since $(M_n, \varphi_n)^\omega \sim p((\prod \varphi_n)\omega)$, it suffices to show that $\prod M_n$ has QWEP. Since each $M_n$ has QWEP, by [Kir93, Corollary 3.3 (i)], $\ell^\infty(N, M_n)$ has QWEP, so does its quotient $(M_n)_\omega$. Therefore $((M_n)_\omega)^\omega$ has QWEP too [Kir93, Corollary 3.3 (v)]. Since $\prod M_n = \pi_\omega(\ell^\infty(N, M_n))''$ is a corner of $((M_n)_\omega)^\omega$, it has QWEP. □

Proof of Theorem 4.2. (1)⇒(2): Assume $M \in \mathcal{F}_{\text{inj}}$. By Theorem 3.4, there is an embedding $i : M \to R_{\text{inj}}$ with a normal faithful conditional expectation $\varepsilon : R_{\text{inj}} \to i(M)$. By Lemma 4.3, $R_{\text{inj}}$ has QWEP, whence $M$ has QWEP.

(2)⇒(1): Let $M = \mathcal{vN}(H)$ with QWEP. We reduce the problem to the case where von Neumann algebras involved are of finite type using the reduction method from [HJX10]. Consider $G = \mathbb{Z}[[\frac{1}{2}]]$ as a countable discrete subgroup of $\mathbb{R}$, and fix $\varphi \in S_{\text{supf}}(M)$. Consider the dual state $\varphi^*$ on $N^\ast = M \rtimes_\varphi G$. There is a canonical embedding $\pi : M \to N$, and as $G$ is countable discrete, there is a normal faithful conditional expectation $\varepsilon : N \to \pi(M)$. By [HJX10, Theorem
2.1], there exists an increasing sequence \( \{N_n\}_{n=1}^{\infty} \) of finite von Neumann subalgebras of \( N \) with \( \sigma_0^* \)-dense union, together with a unique normal faithful conditional expectation \( \varepsilon_n : N \to N_n \) \((n \in \mathbb{N})\) such that

\[
\hat{\varphi} \circ \varepsilon_n = \hat{\varphi}, \quad \sigma_t \circ \varepsilon_n = \varepsilon_n \circ \sigma_t^n, \quad (t \in \mathbb{R}).
\]

Moreover, it holds that (by [HJX10, Lemma 2.7])

\[
\sigma_0^*- \lim_{n \to \infty} \varepsilon_n(x) = x, \quad x \in N.
\]  

(9)

Let \( \theta \) be the dual action of \( \sigma^0|_G \) on \( N \). Then by Takesaki duality, \( N \) is isomorphic to the fixed point subalgebra of the QWEP algebra \( N \rtimes_{\theta} \hat{G} \cong M_{\mathbb{B}(L^2(G))} \) by the dual action of \( \theta \). Since \( \hat{G} = G \) is amenable, there is a conditional expectation of \( N \rtimes_{\theta} \hat{G} \) onto \( N \), so \( N \) has QWEP as well. Again by the existence of \( \varepsilon_n \), each \( N_n \) has QWEP too. Since \( N_n \) is of finite type, by [Kir93, Theorem 4.1], there is an embedding \( i_n : N_n \to R^\omega \) (and a normal faithful conditional expectation \( \varepsilon_n : R^\omega \to i_n(N_n) \)), which automatically exists. Note also that there is an embedding \( i : N \) of \( R \) into \( R \overline{\otimes} R_\infty \cong R_\infty \) and there is a normal faithful conditional expectation \( \varepsilon : R \overline{\otimes} R_\infty \to R \) given by a right-slice map by some \( \varphi \in S_{\text{ut}}(R_\infty) \). Let \( \tau \) be the unique tracial state on \( R \), and let \( \psi := \tau \circ \varepsilon \). Then for any \( (x_n)_n \in \ell^\infty(N,R) \), \((i(x_n))_n \) is in \( M_{\omega}(R_\infty) \) (because \( i(x_n) \) is in \( (R_\infty)_0 \)), whence we have an embedding \( i^\omega : R^\omega \to R_{\infty}^\omega, (x_n)^\omega \mapsto (i(x_n))^\omega \), and a normal faithful conditional expectation \( \varepsilon^\omega : R_{\infty}^\omega \to R_{\infty}^\omega \) given by \( (x_n)^\omega \mapsto (\varepsilon(x_n))^\omega \).

Therefore there is an embedding \( i_n^\omega = i^\omega \circ i_n : N_n \to R_{\infty}^\omega \) and a normal faithful conditional expectation \( \varepsilon_n^\omega = i_n^\omega \circ \varepsilon_n \circ (i^\omega)^{-1} \circ \varepsilon^\omega : R_{\infty}^\omega \to i_n^\omega(N_n) \). Then by Theorem 3.4, \( N_n \in \mathcal{T}_{\text{min}} \) holds. Now, as each \( N_n \) is in \( \text{SA}_\mathcal{F}(N) \) and \( \varepsilon_n \) is the \( \sigma_0^\omega \)-preserving conditional expectation, the argument before [HW98, Corollary 2.12] gives \( N_n \to N \) in \( \text{vN}(H) \). This shows that \( N \in \mathcal{T}_{\text{min}} \). Then by Theorem 3.4, there is an embedding \( j : N \to R_{\infty}^\omega \) with a normal faithful conditional expectation \( \varepsilon^j : R_{\infty}^\omega \to j(N) \) together with a normal faithful conditional expectation \( R_{\infty}^\omega \cong j(N) \overset{j \circ \varepsilon^{-1}}\to i(M) \). Again by Theorem 3.4, \( M \in \mathcal{T}_{\text{min}} \) holds.

\[ \square \]

**Remark 4.4.** Although QWEP conjecture has not been settled, we remark that if there is at least one \( M \in \text{vN}(H) \) without QWEP, then the set \( \text{vN}(H)^{-\text{QWEP}} \) of those \( M \in \text{vN}(H) \) without QWEP, is an open and dense subset of \( \text{vN}(H) \). Indeed, by Theorem 4.2, \( \text{vN}(H)^{-\text{QWEP}} \) is an open set. Suppose there is one \( M \in \text{vN}(H) \) without QWEP, and let \( N \in \text{vN}(H) \). Then by choosing \( v_0 \in \mathcal{U}(H \otimes H, H) \), [HW00, Lemma 2.4], there is \( (u_n)_n \in \mathcal{U}(H \otimes H) \) such that \( v_0 u_n^* (N \overline{\otimes} M) u_n v_0^* \to N \) in \( \text{vN}(H) \). Since \( v_0 u_n^* (N \overline{\otimes} M) u_n v_0^* \) fails QWEP for each \( n \in \mathbb{N}, N \in \text{vN}(H) \), it is in the closure of \( \text{vN}(H)^{-\text{QWEP}} \).

**Theorem 4.5.** Let \( M \) be a von Neumann algebra with separable predual, and let \( \mathcal{P}_M \) be the natural cone in the standard form or \( M \). The following conditions are equivalent.

1. \( M \) has QWEP.

2. For any \( n \in \mathbb{N}, \xi_1, \ldots, \xi_n \in \mathcal{P}_M \), and \( \varepsilon > 0 \), there exists \( k \in \mathbb{N} \) and \( a_1, \ldots, a_n \in M_k(\mathbb{C})_+ \) such that

\[
|\langle \xi_i, \xi_j \rangle - \text{tr}_k(a_i a_j)| < \varepsilon \quad (i, j = 1, \ldots, n).
\]
Here, $tr_k$ is the normalized trace on $M_k(\mathbb{C})$.

Note that if $M$ is a II$_1$ factor, then $P^2_M = M_+\xi_R$. Therefore the above theorem is analogous to the following Kirchberg’s result [Kir93, Proposition 4.6] when unitaries in his results are replaced by positive elements.

**Theorem 4.6** (Kirchberg). Let $M$ be a finite von Neumann algebra with separable predual with a normal faithful tracial state $\tau_M$. Then the following conditions are equivalent:

1. There exists an embedding $i: M \to R^\omega$ with $\tau_M(i(a)) = \tau_M(a)$ ($a \in M$).
2. For every $\varepsilon > 0$, $n \in \mathbb{N}$ and $u_1, \ldots, u_n \in \mathcal{U}(M)$, there is $k \in \mathbb{N}$ and $v_1, \ldots, v_n \in \mathcal{U}(M_k(\mathbb{C}))$ such that
   \[ |\tau_M(u_i^*u_j) - tr_k(u_i^*v_j)| < \varepsilon, \quad |\tau_M(u_i) - tr_k(v_i)| < \varepsilon \]
   for $i, j = 1, \ldots, n$.

The next lemma plays the key role in the proof of Theorem 4.5

**Lemma 4.7.** Let $(M, H_M, J_M, P^2_M), (N, H_N, J_N, P^2_N)$ be standard forms. Assume that $M$ has QWEP, $N$ is $\sigma$-finite and there is a linear isometry $\rho: H_N \to H_M$ satisfying $\rho(P^2_N) \subset P^2_M$. Then $N$ has QWEP.

To prove the lemma, we use following classical results on the natural cone.

**Lemma 4.8** (Araki). Let $(M, H, J, P^2_M)$ be a standard form with $M$ $\sigma$-finite. Let $\varphi \in S_M(M)$ with $\varphi = \omega_\xi$, $\xi \varphi \in P^2_M$. Then $\Phi: M_{sa} \ni a \mapsto \Delta^\frac{1}{2} a \xi \varphi \in P^2_M$ induces an order isomorphism between \{ $a \in M_{sa}$; $-\alpha 1 \leq a \leq \alpha 1$ \} and \{ $\xi \in H$; $J\xi = \xi, -\alpha \xi \varphi \leq \xi \leq \alpha \xi \varphi$ \} for each $\alpha > 0$.

**Proof.** For $a \in M$, it is easy to see that
\[ a \in M_+ \iff \Delta^\frac{1}{2} a \xi \varphi \in P^2_M. \]
This implies that $\Phi$ is an order isomorphism from $M_{sa}$ onto $\Phi(M_{sa})$. By [Ara74, Theorem 3.8 (8)], $\Phi$ maps \{ $x \in M$; $0 \leq x \leq \alpha 1$ \} onto \{ $\eta \in P^2_M$; $0 \leq \eta \leq \alpha \xi \varphi$ \}. From this the claim easily follows.

**Lemma 4.9.** Let $(M, H, J, P^2)$ be a standard form. For each $\xi \in P^2$, denote by $e(\xi)$ the support projection of $\omega_\xi$. Let $q := e(\xi)Je(\xi)J$. Then the following holds.

1. (Araki) $\xi \perp \eta \iff e(\xi) \perp e(\eta)$.
2. For $\xi, \eta \in P^2$, $e(\xi) \leq e(\eta)$ if and only if $\eta \perp \xi \perp \zeta$ holds for every $\zeta \in P^2$.
3. $q(P^2) = (\{ \xi \}^\perp \cap P^2)^\perp \cap P^2$.

**Proof.** (1) ($\Rightarrow$) is [Ara74, Theorem 4, (7)], while ($\Leftarrow$) is clear. (2) and (3) have been known. We include a proof from second named author’s master thesis for reader’s convenience.

(2) ($\Rightarrow$) follows from (1). ($\Leftarrow$) Let $\{ \xi_i \}_{i \in I}$ be a family of elements in $P^2_M$ such
that \( \{e(\xi_i)\}_{i \in I} \) are pairwise orthogonal and \( \sum_{i \in I} e(\xi_i) = 1 - e(\eta) \) (it can be proved that every \( \sigma \)-finite projection \( p \in M \) is of the form \( p = e(\eta) \) for some \( \eta \in \mathcal{P}^2_M \)). Hence \( \xi_i \perp \eta \), which implies that \( \xi_i \perp \xi \) for all \( i \in I \). By (1), \( e(\xi_i) \perp e(\xi) \) \( (i \in I) \) holds. Therefore

\[
e(\xi) \leq 1 - \sum_{i \in I} e(\xi_i) = e(\eta).
\]

(3) By (2), it holds that for \( \eta \in \mathcal{P}^2_M \),

\[
e(\eta) \leq e(\xi) \iff \forall \zeta \in \mathcal{P}^2_M (\zeta \perp \xi \Rightarrow \zeta \perp \eta)
\]
\[
\iff \eta \in (\{\xi\} \cap \mathcal{P}^2_M)^\perp \cap \mathcal{P}^2_M.
\]

If \( e(\eta) \leq e(\xi) \), then \( e(\xi) \eta = \eta \), so \( q \eta = Je(\xi)Je(\xi) \eta = Je(\xi) \eta = \eta = \eta \). Thus, \( \eta = q(\eta) \in q(\mathcal{P}^2_M) \). On the other hand, if \( \eta \in q(\mathcal{P}^2_M) \), then clearly \( e(\eta) \leq e(\xi) \) holds. This shows that \( q(\mathcal{P}^2_M) = (\{\xi\} \cap \mathcal{P}^2_M)^\perp \cap \mathcal{P}^2_M \).

The next result is [Oz04, Corollary 5.3].

**Lemma 4.10** ([Kir93, Oz04]). Let \( M \) be a von Neumann algebra, and if there is a \( C^* \)-algebra \( A \) with QWEP and a contractive linear map \( \varphi : A \rightarrow M \) such that \( \varphi(\text{Ball}(A)) \) is ultraweakly dense in \( \text{Ball}(M) \), then \( M \) has QWEP.

**Proof of Lemma 4.7.** Put \( e := \rho p^* \in \mathbb{B}(H_M) \).

**Claim 1.** \( \rho(\mathcal{P}^2_N) = e(\mathcal{P}^2_M) = \mathcal{P}^2_M \cap e(H_M), \) and \( \rho J_N = J_M p \).

First, \( \rho(\mathcal{P}^2_N) = \rho(\mathcal{P}^2_N) \cap e(H_M) \) holds. To prove \( e(\mathcal{P}^2_M) \subseteq \rho(\mathcal{P}^2_N) \), we show \( \rho^*(\mathcal{P}^2_M) \subseteq \mathcal{P}^2_N \). For each \( \eta \in \mathcal{P}^2_M \), we have \( \langle \rho^*(\xi), \eta \rangle = \langle \xi, \rho(\eta) \rangle \geq 0 \), because \( \rho(\eta) \in \mathcal{P}^2_M \), whence \( \rho^*(\xi) \in (\mathcal{P}^2_M)^0 = \mathcal{P}^2_M \) and \( \rho^*(\mathcal{P}^2_M) \subseteq \mathcal{P}^2_N \) holds. Therefore for \( \xi \in \mathcal{P}^2_M, e\xi = \rho(\rho^*\xi) \in \rho(\mathcal{P}^2_N) \). This proves \( \rho(\mathcal{P}^2_N) = e(\mathcal{P}^2_M) \). Note that this also shows that \( e(\mathcal{P}^2_M) \subseteq \mathcal{P}^2_M \). Therefore \( e(\mathcal{P}^2_M) = \mathcal{P}^2_M \cap e(H_M) \) holds too. To see that last equality, recall that any \( \xi \in H_N \) can be written as \( \xi = (\xi_1 - \xi_2) + i(\xi_3 - \xi_4) \), where \( \xi_j \in \mathcal{P}^2_N \) and \( J_N \xi_j = \xi_j \) \((1 \leq j \leq 4)\). From this it holds that

\[
\rho J_N \xi = \rho \{ (\xi_1 - \xi_2) - i(\xi_3 - \xi_4) \} = J_M \{ (\rho \xi_1 - \rho \xi_2) + i(\rho \xi_3 - \rho \xi_4) \}
\]
\[
= J_M \rho \xi.
\]

Now fix \( \psi \in \text{Sud}(N) \). Then \( \psi = \omega_{\xi_\psi}, \xi_\psi \in \mathcal{P}^2_N \). Let \( \varphi := \omega_\eta, \eta := \rho(\xi_\psi) \in \mathcal{P}^2_M \), and \( p := \text{supp}(\varphi) \in M \).

**Claim 2.** \( q := \rho J_M p J_M \geq e \).

Since \( H_M \) is spanned by \( \mathcal{P}^2_M \), it suffices to show that \( q(\mathcal{P}^2_M) \supset q(\mathcal{P}^2_M) = \rho(\mathcal{P}^2_N) \).

Let \( \xi \in \mathcal{P}^2_N \). Let \( \zeta \in \{\rho(\xi_\psi)\}^0 \cap \mathcal{P}^2_M \). Then \( 0 = \langle \zeta, \rho(\xi_\psi) \rangle = \langle \rho^*(\xi), \xi_\psi \rangle \). Since \( \psi = \omega_{\xi_\psi} \) is faithful, by Lemma 4.9 (1), \( \zeta \perp \xi_\psi \Rightarrow \zeta \perp \xi \) holds for every \( \zeta \in \mathcal{P}^2_N \). Therefore \( \rho^*(\xi) \perp \xi \Rightarrow \zeta \perp \rho(\xi) \) holds. This implies, by Lemma 4.9 (3), that

\[
\rho(\xi) \in \{\rho(\xi_\psi)\}^0 \cap \mathcal{P}^2_M = q(\mathcal{P}^2_M).
\]

Therefore \( e(\mathcal{P}^2_M) = \rho(\mathcal{P}^2_N) \subseteq q(\mathcal{P}^2_M) \), and \( e \leq q \) holds.
Since $M$ has QWEP, so does $qMq$. Therefore we may replace $(M, H_M, J_M, P^2_M)$ by $(qMq, qH_M, J_M, q(P^2_M))$ and assume that $q = 1$, and $\varphi$ is faithful on $M$ with $\xi_\varphi = \rho(\xi_\varphi) \in P^2_M$. In this case we may identify $P^2_M = \Delta^\frac{1}{2} M + \xi_\varphi$, $P^2_N = \Delta^\frac{1}{2} N + \xi_\varphi$.

Claim 3. There are unital positive maps $i: N \to M, \varepsilon: M \to N$ such that the following diagram commutes.

\[
\begin{array}{ccc}
N_+ & \overset{i}{\longrightarrow} & M_+ \\
\downarrow{\beta} & & \downarrow{\alpha} \\
\mathcal{P}^2_N & \overset{\rho}{\longrightarrow} & \mathcal{P}^2_M \\
\downarrow{\rho^*} & & \downarrow{\rho^*} \\
\mathcal{P}^2_N & \overset{\rho}{\longrightarrow} & \mathcal{P}^2_M \\
\end{array}
\]

where $\alpha: M_+ \ni x \mapsto \Delta^\frac{1}{2} x \xi_\varphi \in \mathcal{P}^2_M, \beta: N_+ \ni y \mapsto \Delta^\frac{1}{2} y \xi_\varphi \in \mathcal{P}^2_N$. To construct $i$, let $y \in N_+$. Then as $0 \leq y \leq \|y\|1$, Lemma 4.8 asserts that $\Delta^\frac{1}{2} y \xi_\varphi \leq \|y\|\xi_\varphi$ in $\mathcal{P}^2_M$. Therefore $\rho(\Delta^\frac{1}{2} y \xi_\varphi) \leq \rho(\|y\|\xi_\varphi) = \|y\|\xi_\varphi$ in $\mathcal{P}^2_M$ holds. Again by Lemma 4.8 applied to $\mathcal{P}^2_M$, there exists unique $\theta(y) \in M_+, 0 \leq \|\theta(y)\| \leq \|y\|$, such that $\rho(\Delta^\frac{1}{2} y \xi_\varphi) = \Delta^\frac{1}{2} \theta(y) \xi_\varphi$. It is clear from the construction that $N_+ \ni y \mapsto \theta(y) \in M_+$ is an affine map. Let now $y \in N$. There exist unique $y_k \in N_+(1 \leq k \leq 4)$ with $y_1 y_2 = y_2 y_1 = 0 = y_3 y_4 = y_4 y_3$ such that $y = (y_1 - y_2) + i(y_3 - y_4)$. Then define

\[
i(y) := (\theta(y_1) - \theta(y_2)) + i(\theta(y_3) - \theta(y_4)).
\]

Then $i: N \to M$ is a positive linear map. Similarly, we define $\varepsilon$ by

\[
\varepsilon(x) := (\pi(x_1) - \pi(x_2)) + i(\pi(x_3) - \pi(x_4)),
\]

for $x = (x_1 - x_2) + i(x_3 - x_4)$ with $x_k \in M_+(1 \leq k \leq 4), x_1 x_2 = x_2 x_1 = 0 = x_3 x_4 = x_4 x_3$, where for $x \in M_+, \pi(x) \in N_+$ is the unique element satisfying

\[
\rho^*(\Delta^\frac{1}{2} x \xi_\varphi) = \Delta^\frac{1}{2} \pi(x) \xi_\varphi.
\]

Note that since $\rho^*(\mathcal{P}^2_M) \subset \mathcal{P}^2_N$, $\pi(x)$ is well-defined by Lemma 4.8. By construction, the above diagram commutes. Finally, let $y \in N_+$. Then by construction, $\rho(\Delta^\frac{1}{2} y \xi_\varphi) = \Delta^\frac{1}{2} i(y) \xi_\varphi$ holds. Then we apply $\rho^*$ to obtain $\Delta^\frac{1}{2} y \xi_\varphi = \rho^*(\Delta^\frac{1}{2} i(y) \xi_\varphi)$. Therefore by the construction of $\varepsilon, \varepsilon \circ i(y) = y$ holds. Therefore by linearity, $\varepsilon \circ i = id_{N_+}$.

Proof of Theorem 4.5. (1)$\Rightarrow$(2) Assume that $M$ has QWEP, then by Theorem 4.2, $M \in \mathcal{F}_{in}$ holds. By (the proof of) [HW00, Corollary 2.11], the set $\mathcal{F}_{in}$ of finite type I factors is dense in $\mathcal{F}_{in}$. Therefore there is $\{k_n\}_{n=1}^\infty \subset N$ and $N_n \in \text{vN}(H)$ with $N_n \cong M_{k_n}(\mathbb{C})$ ($n \in N$) such that $N_n \to M$ in $\text{vN}(H)$. Then by Theorem 3.1, there is $\varphi_n \in S_{\text{opt}}(M_{k_n}(\mathbb{C}))$ ($n \in N$), an embedding $i: M \to (M_{k_n}(\mathbb{C}), \varphi_n)\omega$, and a normal faithful conditional expectation $\varepsilon: (M_{k_n}(\mathbb{C}), \varphi_n)\omega \to i(M)$. Let $(M_{k_n}(\mathbb{C}), K_n, J_n, \mathcal{P}^2_n)$ be the standard
form constructed from the GNS representation of \( \varphi_n \) for each \( n \in \mathbb{N} \). Then by [AH12, Theorem 3.18], \( \{\prod_k M_{b_k}(\mathbb{C}), K_n, J_n, P_n^\omega\} \) is a standard form, where \( (K_n, J_n, P_n^\omega) \) is the ultraproduct of \( (K_n, J_n, P_n^\omega) \) (see [AH12, Theorem 3.18]).

Let \( p = \text{supp}(\langle \varphi_n \rangle) = \prod_k M_{b_k}(\mathbb{C}) \), and \( q := pJ_qpJ_q \). Then by [AH12, Corollaries 3.27 and 3.28], \( (q, [\prod_k M_{b_k}(\mathbb{C})]_q, qK_n, J_n[qK_n, qP_n^\omega]) \) can be regarded as a standard representation of \( M = (M_{b_k}(\mathbb{C}), \varphi_n)^\omega \). Recall also that the natural cone \( P_n^\omega \) can be also regarded as the one constructed from the GNS representation of the trace \( tr_k \); we see that \( P_n^\omega \) satisfies condition (2) for each \( n \). Then \( P_n^\omega \) also satisfies condition (2): let \( \varepsilon > 0, m \in \mathbb{N} \) and \( \xi_1 = (\xi_{i,n}), \cdots, \xi_m = (\xi_{i,n}) \in P_n^\omega \) be given, where \( \xi_{i,n} \in P_n^\omega \) (\( 1 \leq i \leq m, n \in \mathbb{N} \)). Then we have

\[
\langle \xi_i, \xi_j \rangle = \lim_{n \to \omega} \langle \xi_{i,n}, \xi_{j,n} \rangle = \lim_{n \to \omega} tr_k(\xi_{i,n}\xi_{j,n})(1 \leq i, j \leq m),
\]

so that

\[
J := \{n \in \mathbb{N}; |\langle \xi_i, \xi_j \rangle - tr_k(\xi_{i,n}\xi_{j,n})| < \varepsilon, 1 \leq i, j \leq m\} \in \omega.
\]

Choose \( n_0 \in J \), and put \( \eta_i := \xi_{i,n_0} \) (\( 1 \leq i \leq m \)). Then the inequality in (2) is satisfied. But as \( q(P_n^\omega) \subset P_n^\omega \), \( q(P_n^\omega) \) also satisfies (2). Furthermore, \( i(M) < \tilde{M} \) and we have a normal faithful conditional expectation \( \varepsilon : \tilde{M} \to i(M) \). Thus choosing \( \psi \in S_{sa}(i(M)) \) and letting \( \psi := \psi \circ \varepsilon \), we obtain

\[
P_M^\omega \cong P^\omega_{i(M)} = \Delta^4_{\psi}i(M)\xi_{\psi} \subset P^\omega_{\tilde{M}} = \Delta^4_{\psi}M\xi_{\psi} \cong q(P^\omega_{i(M)}).
\]

Here, \( \cong \) means that the one natural cone is mapped to the other by a unitary implementing the isomorphism of a standard form. Therefore \( P_M^\omega \) satisfies condition (2).

(2) \( \Rightarrow \) (1) Assume \( M \) satisfies (2). Let \( \{\xi_n\}_{n=1}^\infty \subset P_M^\omega \) be a dense sequence. Using condition (2), for each \( n \in \mathbb{N} \), choose \( k_n \in \mathbb{N} \) and \( a_{i,n}, a_{j,n} \in M_{b_k}(\mathbb{C})_{+} \) such that

\[
|\langle \xi_i, \xi_j \rangle - tr_k(a_{i,n}^{(n)}a_{j,n}^{(n)})| < \frac{1}{n}, \quad 1 \leq i, j \leq n.
\]

Put

\[
\xi_i := \begin{cases} a_{i,n}^{(n)}\xi_{tr_k} \in P_n^\omega := P_{M_{b_k}(\mathbb{C})} \quad (n \geq i) \\ 0 \quad (n < i), \end{cases}
\]

and \( \tilde{\xi}_i := (\xi_i^{(n)})_{\omega} \in P_n^\omega := (P_n^\omega)_{\omega} \). Then

\[
\langle \tilde{\xi}_i, \tilde{\xi}_j \rangle = \lim_{n \to \omega} \langle \xi_i^{(n)}, \xi_j^{(n)} \rangle = \langle \xi_i, \xi_j \rangle, \quad i,j \in \mathbb{N}.
\]

Fix one \( \varphi \in \text{nf}(M) \). Then on the dense subspace \( K_0 := \text{span}\{\xi_i; i \geq 1\} \) of \( L^2(M, \varphi) \), define \( \rho_0 : K_0 \to H_\omega \) by

\[
\rho_0 \left( \sum_{j=1}^k \lambda_j \xi_{i,j} \right) := \sum_{j=1}^k \lambda_j \tilde{\xi}_{i,j}, \quad \lambda_{i,j} \in \mathbb{C} \quad (1 \leq i \leq k).
\]

Then \( \rho_0 \) is uniquely extended to a linear isometry \( \rho : L^2(M, \varphi) \to H_\omega \) such that \( \rho(P_M^\omega) \subset P_\omega \). Since \( \tilde{M} := \prod_k M_{b_k}(\mathbb{C}) \) has QWEP with natural cone \( P_\omega \), \( M \) has QWEP thanks to Lemma 4.7. \( \square \)
As a corollary, we have the following:

**Theorem 4.11.** Let $0 < \lambda < 1$. The following conditions are equivalent:

(a) $\mathcal{F}_{\text{inj}}$ is dense in $\mathcal{vN}(H)$.

(b) For any $N \in \mathcal{vN}(H)$, there is an embedding $i : N \to R_\omega^\infty$ and a normal faithful conditional expectation $\varepsilon : R_\omega^\infty \to i(N)$.

(c) For any $N \in \mathcal{vN}(H)$, there is an embedding $i : N \to R_\lambda^\infty$ and a normal faithful conditional expectation $\varepsilon : R_\lambda^\infty \to i(N)$.

(d) For any $N \in \mathcal{F}_{\text{II}}$, there is an embedding $i : N \to R^\omega$.

(e) Every $N \in \mathcal{vN}(H)$ has QWEP.

(f) For any $N \in \mathcal{vN}(H)$, there is $\{n_k\}_{k=1}^\infty \subseteq \mathbb{N}$, a sequence $\varphi_k \in S_{\text{af}}(M_{n_k}(\mathbb{C}))$ such that $N$ admits an embedding $i : N \to (M_{n_k}(\mathbb{C}), \varphi_k)^\omega$ and a normal faithful conditional expectation $\varepsilon : (M_{n_k}(\mathbb{C}), \varphi_k)^\omega \to i(N)$.

**Acknowledgements**

The authors thank Masaki Izumi for useful comments and informations about literature. HA is supported by EPDI/JSPS/IHÉS Fellowship. UH is supported by ERC Advanced Grant No. OAFPG 27731 and the Danish National Research Foundation through the Center for Symmetry and Deformation.

**Appendix**

In this appendix we add proofs for the following lemmata. Both of them have been known, and the latter is essentially due to Araki [Ara74]. We include proofs for reader’s convenience.

**References**


