

A CONTRACTIVE VERSION OF A SCHUR-HORN THEOREM IN II_1 FACTORS

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ABSTRACT. We prove a contractive version of the Schur-Horn theorem for submajorization in II_1 factors that complements some previous results on the Schur-Horn theorem within this context. We obtain a reformulation of a conjecture of Arveson and Kadison regarding a strong version of the Schur-Horn theorem in II_1 factors in terms of submajorization and contractive orbits of positive operators.

1. INTRODUCTION

Vector and matrix majorization theory play an important role in matrix analysis, mostly as a tool in the study of general (convex) inequalities, unitarily invariant norm inequalities, geometry, and problems related with the description of the diagonals of matrix representations of a linear operator [1, 2, 4, 12]. Some historical aspects of the theory of majorization are mentioned in [3, 5]. The Schur-Horn theorem, coined in the papers [8, 15], is probably the most remarkable among the many characterizations known for these notions (see the precise statement of the theorem after Proposition 2.3). It is thus natural to search for analogues of this result in contexts where majorization theory has been extended [5, 6, 7, 10, 13]. Among these analogues let us mention the work of Neumann [13] for selfadjoint operators in $\mathcal{B}(\mathcal{H})$, the refinements of Kadison [11] in the case of projectors in $\mathcal{B}(\mathcal{H})$, and the recent work [5].

The fact that II_1 factors share many structural properties with the algebra of linear operators acting on \mathbb{C}^n makes them a natural context in which to extend majorization. In [5], Arveson and Kadison posed a (strong) version of the Schur-Horn theorem for II_1 factors as a problem and proved related results. As a first step toward settling the Arveson-Kadison problem, the authors have proven in [3] a weaker version, related with the point of view developed in [13]. In this note we obtain a weak contractive version of submajorization within II_1 factors in the spirit of [3] (Theorem 3.4). We also obtain an equivalent reformulation of the Arveson-Kadison problem (Theorem 4.1) using a characterization of spectral dominance and submajorization (Proposition 3.1).

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2. PRELIMINARIES

Throughout the paper \mathcal{M} denotes a II_1 factor with normalized faithful normal trace τ . We denote by \mathcal{M}^{sa} , \mathcal{M}^+ , $\mathcal{U}_{\mathcal{M}}$, the sets of selfadjoint, positive, and unitary elements of \mathcal{M} . Given $a \in \mathcal{M}^{\text{sa}}$ we denote its spectral measure by p^a . The characteristic function of the set Δ is denoted by 1_{Δ} . We denote integration with respect to Lebesgue measure by dt .

Besides the usual operator norm in \mathcal{M} , we consider the Schatten norm induced by the trace, $\|x\|_1 = \tau(|x|)$. As we will be always dealing with bounded sets in a II_1 factor, we can profit from the fact that the topology induced by the Schatten norm agrees with the σ -strong operator topology. Because of this we will express our results in terms of σ -strong closures although our computations are based on estimates for the Schatten norm. For $X \subset \mathcal{M}$, we shall denote by \overline{X} and $\overline{X}^{\sigma\text{-sot}}$ the respective closures in the norm topology and in the σ -strong operator topology. For any set K , $\text{co}K$ denotes its convex hull.

2.1. Spectral scale and spectral preorders. The *spectral scale* [14] of $a \in \mathcal{M}^{\text{sa}}$ is defined by

$$\lambda_a(t) = \min\{s \in \mathbb{R} : \tau(p^a(s, \infty)) \leq t\}, \quad t \in [0, 1].$$

The function $\lambda_a : [0, 1] \rightarrow \mathbb{R}$ is non-increasing and right-continuous. The map $a \mapsto \lambda_a$ is continuous both with respect to $\|\cdot\|$ and $\|\cdot\|_1$, since [14]

$$(1) \quad \|\lambda_a - \lambda_b\|_{\infty} \leq \|a - b\|, \quad \|\lambda_a - \lambda_b\|_1 \leq \|a - b\|_1 \quad a, b \in \mathcal{M}^{\text{sa}},$$

where the norms on the left are those of $L^{\infty}([0, 1], dt)$ and $L^1([0, 1], dt)$ respectively. A useful property of the spectral scale is that we can use it to recover the trace, in the following sense:

$$(2) \quad \tau(a) = \int_0^1 \lambda_a(t) dt.$$

The unitary orbit of $a \in \mathcal{M}^{\text{sa}}$ is the set $\mathcal{U}_{\mathcal{M}}(a) = \{u^*au : u \in \mathcal{U}_{\mathcal{M}}\}$. It is straightforward from the definition of the spectral scale that if $b \in \mathcal{U}_{\mathcal{M}}(a)$, then $\lambda_a = \lambda_b$. By the continuity (1), $\lambda_b = \lambda_a$ for any b in the $\|\cdot\|_1$ -closure or the $\|\cdot\|$ -closure of the unitary orbit of $a \in \mathcal{M}^{\text{sa}}$. A converse of this fact was proven by Kamei. We summarize this information for future reference:

Theorem 2.1 ([9]). *If $a \in \mathcal{M}^{\text{sa}}$, then*

$$\overline{\mathcal{U}_{\mathcal{M}}(a)} = \overline{\mathcal{U}_{\mathcal{M}}(a)}^{\sigma\text{-sot}} = \{b \in \mathcal{M}^{\text{sa}} : \lambda_a = \lambda_b\}.$$

Let $a, b \in \mathcal{M}^{\text{sa}}$. We say that a is *spectrally dominated* by b , written $a \preceq b$, if any of the following (equivalent) statements holds:

- (i) $\lambda_a(t) \leq \lambda_b(t)$, for all $t \in [0, 1]$.
- (ii) $\tau(p^a(t, \infty)) \leq \tau(p^b(t, \infty))$, for all t .

We say that a is *submajorized* by b , written $a \prec_w b$, if

$$\int_0^s \lambda_a(t) dt \leq \int_0^s \lambda_b(t) dt, \quad \text{for every } s \in [0, 1].$$

If in addition $\tau(a) = \tau(b)$ then we say that a is *majorized* by b , written $a \prec b$.

Remark 2.2. Let $a, b \in \mathcal{M}^{\text{sa}}$. It is known [14] that

(i) if $a \leq b$ then $a \preceq b$. Thus, using this and (2),

$$a \leq b \Rightarrow a \preceq b \Rightarrow a \prec_w b \Rightarrow \tau(a) \leq \tau(b);$$

(ii) if $v \in \mathcal{M}$ is a contraction ($\|v\| \leq 1$) then $v^*av \preceq a$.

If $\mathcal{N} \subset \mathcal{M}$ is a von Neumann subalgebra and $b \in \mathcal{M}^{sa}$, we denote by $\Omega_{\mathcal{N}}(b)$ and $\Theta_{\mathcal{N}}(b)$ the sets of elements in \mathcal{N}^{sa} that are respectively majorized and submajorized by b , i.e.

$$\Omega_{\mathcal{N}}(b) = \{a \in \mathcal{N}^{sa} : a \prec b\}, \quad \Theta_{\mathcal{N}}(b) = \{a \in \mathcal{N}^{sa} : a \prec_w b\}.$$

The following result was proven in [3].

Proposition 2.3. *Let $b \in \mathcal{B}^{sa}$, where $\mathcal{B} \subset \mathcal{M}$ is a diffuse abelian von Neumann subalgebra. Then there exists a spectral resolution $\{e(t)\}_{t \in [0,1]} \subset \mathcal{B}$ with $\tau(e(t)) = t$ for every $t \in [0,1]$, and such that*

$$b = \int_0^1 \lambda_b(t) de(t).$$

The classical Schur-Horn theorem states that if \mathcal{N} is a type I_n factor, $\mathcal{D} \subset \mathcal{N}$ is a masa, $E_{\mathcal{D}}$ is the canonical projection onto \mathcal{D} , and $b \in \mathcal{N}^{sa}$, then

$$E_{\mathcal{D}}(\mathcal{U}_{\mathcal{N}}(b)) = \Omega_{\mathcal{D}}(b).$$

In [3], the authors proved the following related result for II_1 factors.

Theorem 2.4. *Let $\mathcal{A} \subset \mathcal{M}$ be a diffuse abelian von Neumann subalgebra and let $b \in \mathcal{M}^{sa}$. Then*

$$(3) \quad \overline{E_{\mathcal{A}}(\mathcal{U}_{\mathcal{M}}(b))}^{\sigma\text{-}so} = \Omega_{\mathcal{A}}(b).$$

3. A CONTRACTIVE VERSION OF THE SCHUR-HORN THEOREM

Given $x \in \mathcal{M}$ we shall consider its contractive orbit $\mathcal{C}_{\mathcal{M}}(x)$, namely

$$\mathcal{C}_{\mathcal{M}}(x) := \{v^*xv : v \in \mathcal{M}, \|v\| \leq 1\}.$$

Using the results quoted in Section 2, we prove the following characterization of submajorization and spectral dominance.

Proposition 3.1. *Let $a, b \in \mathcal{M}^+$. Then*

- (i) $a \prec_w b$ if and only if there exists $c \in \mathcal{M}^+$ such that $a \prec c \leq b$. Moreover, if $\mathcal{B} \subset \mathcal{M}$ is a diffuse abelian von Neumann subalgebra such that $b \in \mathcal{B}^+$, we can choose $c \in \mathcal{B}^+$.
- (ii) $a \preceq b$ if and only if $a \in \overline{\mathcal{C}_{\mathcal{M}}(b)}$.

Proof. (i) Assume first that $a \prec_w b$ and, without loss of generality, assume that $b \in \mathcal{B}$ for a diffuse abelian subalgebra $\mathcal{B} \subseteq \mathcal{M}$. Let $\{e(t)\}_{t \in [0,1]} \subseteq \mathcal{B}$ be a spectral resolution as in Proposition 2.3. Since the function $g(s) := \int_0^s \lambda_b(t) dt$ is continuous and $a \prec_w b$, there exists $s_0 \in [0,1]$ such that $\tau(a) = g(s_0)$. Thus, if we let $c = \int_0^{s_0} \lambda_b(t) de(t)$, it is straightforward to verify that $\lambda_c(t) = 1_{[0,s_0]} \lambda_b(t)$ for $t \in [0,1]$. From this it follows that $a \prec c$. It is also clear that $c \in \mathcal{B}$ and that $c \leq b$. Conversely, if there exists $c \in \mathcal{M}^+$ such that $a \prec c \leq b$, then $a \prec_w c$ and $c \prec_w b$, and so by transitivity we get $a \prec_w b$.

(ii) Let $a, b \in \mathcal{M}^+$ with $a \precsim b$. Let \mathcal{B} be a diffuse abelian subalgebra with $b \in \mathcal{B}$, and let $\{e(t)\}_{t \in [0,1]} \subseteq \mathcal{B}$ be as before. By hypothesis $0 \leq \lambda_a \leq \lambda_b$, so in particular $\{\lambda_b = 0\} \subseteq \{\lambda_a = 0\}$. Thus the function $f = 1_{\{\lambda_b \neq 0\}} \cdot \lambda_a / \lambda_b$ is well defined, $0 \leq f \leq 1$, and $f \cdot \lambda_b = \lambda_a$. Therefore $v = \int_0^1 f(t)^{1/2} de(t) \in \mathcal{B}$ is a contraction such that

$$v^*bv = \int_0^1 \lambda_a(t) de(t) \quad \text{and thus} \quad \lambda_{v^*bv} = \lambda_a.$$

By Theorem 2.1 it follows that $a \in \overline{\mathcal{U}_{\mathcal{M}}(v^*bv)} \subset \overline{\mathcal{C}_{\mathcal{M}}(b)}$. To see the converse, let $a \in \overline{\mathcal{C}_{\mathcal{M}}(b)}$. Then $a \precsim b$ since, by (ii) in Remark 2.2, $v^*bv \precsim b$ for any contraction $v \in \mathcal{M}$, and by (1) the spectral scale is uniformly continuous with respect to the operator norm. \square

In [6, Theorem 3.1], Hiai shows that $\{a \in \mathcal{M} : a \precsim b\} = \overline{\mathcal{C}_{\mathcal{M}}(b)}^{\sigma\text{-sot}}$. So, from Proposition 3.1, we obtain

Corollary 3.2. *If $b \in \mathcal{M}$, then $\overline{\mathcal{C}_{\mathcal{M}}(b)}^{\sigma\text{-sot}} = \overline{\mathcal{C}_{\mathcal{M}}(b)}$.*

Lemma 3.3. *Let $\mathcal{N} \subset \mathcal{M}$ be a von Neumann subalgebra and let $E_{\mathcal{N}}$ be the trace preserving conditional expectation onto \mathcal{N} . Then, for any $b \in \mathcal{M}^+$,*

- (i) $\|E_{\mathcal{N}}(b)\|_1 \leq \|b\|_1$.
- (ii) $\overline{E_{\mathcal{N}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}} \subset \Theta_{\mathcal{N}}(b) \cap \mathcal{N}^+$.

Proof. (i) is proved in [3]. To see (ii) note that by Remark 2.2, for every $v \in \mathcal{M}$ such that $\|v\| \leq 1$, $v^*bv \precsim b$; by Theorem 2.2, in [3], $E_{\mathcal{N}}(v^*bv) \prec v^*bv$. So by transitivity $E_{\mathcal{N}}(v^*bv) \in \Theta_{\mathcal{N}}(b) \cap \mathcal{N}^+$. If $(a_n)_{n \in \mathbb{N}} \subset E_{\mathcal{N}}(\mathcal{C}_{\mathcal{M}}(b))$ is such that $\lim_{n \rightarrow \infty} \|a_n - a\|_1 = 0$ for some $a \in \mathcal{N}$, then necessarily $a \in \mathcal{N}^+$. By the previous argument we have that $a_n \prec_w b$ for every n . Therefore, by (1),

$$\int_0^s \lambda_a(t) dt = \lim_{n \rightarrow \infty} \int_0^s \lambda_{a_n}(t) dt \leq \int_0^s \lambda_b(t) dt,$$

and so $a \prec_w b$. \square

Next we prove our main result, which complements Theorem 2.4 in the case of sub-majorization and contractive orbits.

Theorem 3.4. *Let $\mathcal{A} \subset \mathcal{M}$ be a diffuse abelian von Neumann subalgebra of \mathcal{M} and let $b \in \mathcal{M}^+$. Then*

$$(4) \quad \overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}} = \Theta_{\mathcal{A}}(b) \cap \mathcal{A}^+.$$

Proof. By (ii) in Lemma 3.3, $\overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}} \subset \Theta_{\mathcal{A}}(b) \cap \mathcal{A}^+$. To prove the other inclusion, let $a \in \mathcal{A}^+$ be such that $a \prec_w b$. By (i) in Proposition 3.1 there exists $c \in \mathcal{M}^+$ such that $a \prec c \leq b$. By Theorem 2.4,

$$(5) \quad a \in \overline{E_{\mathcal{A}}(\mathcal{U}_{\mathcal{M}}(c))}^{\sigma\text{-sot}}.$$

Note that, since $c \leq b$, $c \precsim b$ (Remark 2.2). Thus, by (ii) in Proposition 3.1,

$$(6) \quad c \in \overline{\mathcal{C}_{\mathcal{M}}(b)}.$$

Let $\varepsilon > 0$. By (5) and (6) there exist $u \in \mathcal{U}_{\mathcal{M}}$ and a contraction $v \in \mathcal{M}$ such that $\|a - E_{\mathcal{A}}(u^*cu)\|_1 \leq \varepsilon$ and $\|c - v^*bv\| \leq \varepsilon$. Therefore

$$\|E_{\mathcal{A}}(u^*cu) - E_{\mathcal{A}}((vu)^*b(vu))\|_1 = \|E_{\mathcal{A}}(u^*(c - v^*bv)u)\|_1 \leq \varepsilon,$$

since $\|x\|_1 \leq \|x\|$ and $E_{\mathcal{A}} \circ \text{Ad}_u$ is a $\|\cdot\|_1$ -contraction (Lemma 3.3). Thus

$$\begin{aligned} \|a - E_{\mathcal{A}}((vu)^*b(vu))\|_1 &\leq \|a - E_{\mathcal{A}}(u^*cu)\|_1 \\ &\quad + \|E_{\mathcal{A}}(u^*cu) - E_{\mathcal{A}}((vu)^*b(vu))\|_1 \\ &\leq 2\varepsilon. \end{aligned}$$

As ε was arbitrary, we get $a \in \overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}}$, as desired. \square

Corollary 3.5. *For each $b \in \mathcal{M}^+$, the set $\overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}}$ is convex and σ -weakly compact.*

Proof. By (3) in Theorem 2.5 of [6],

$$(7) \quad \Theta_{\mathcal{M}}(b) = \overline{\text{co}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}}.$$

The right-hand side is bounded, convex, and σ -strongly closed, so it is σ -weakly closed and thus compact. Then

$$\Theta_{\mathcal{A}}(b) \cap \mathcal{A}^+ = \Theta_{\mathcal{M}}(b) \cap \mathcal{A}^+ = \overline{\text{co}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}} \cap \mathcal{A}^+$$

is convex and σ -weakly compact. By Theorem 3.4, we are done. \square

Remark 3.6. For any $b \in \mathcal{M}^+$, the property of $\overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}}$ being convex is essentially equivalent to Theorem 3.4. Indeed, assuming $\overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}}$ to be convex and using (7),

$$\begin{aligned} \Theta_{\mathcal{A}}(b) \cap \mathcal{A}^+ &\subset E_{\mathcal{A}}\left(\overline{\text{co}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}}\right) \subset \overline{E_{\mathcal{A}}(\text{co}(\mathcal{C}_{\mathcal{M}}(b)))}^{\sigma\text{-sot}} \\ &= \overline{\text{co}E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}} = \overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}}, \end{aligned}$$

where we have used that $E_{\mathcal{A}}$ is $\|\cdot\|_1$ -continuous (by (i) in Lemma 3.3). The reverse inclusion is given by (ii) in Lemma 3.3.

4. A REFORMULATION OF THE ARVESON-KADISON PROBLEM

Let $\mathcal{A} \subset \mathcal{M}$ be a masa and $b \in \mathcal{M}^+$. In [5], Arveson and Kadison pose the problem of whether

$$(8) \quad E_{\mathcal{A}}(\overline{\mathcal{U}_{\mathcal{M}}(b)}) = \Omega_{\mathcal{A}}(b).$$

Similarly, with regard to the results of the present paper, it is natural to ask whether

$$(9) \quad E_{\mathcal{A}}(\overline{\mathcal{C}_{\mathcal{M}}(b)}) = \Theta_{\mathcal{A}}(b) \cap \mathcal{A}^+.$$

It turns out that the two problems are equivalent, even in the broader class of diffuse abelian subalgebras.

Theorem 4.1. *Let $\mathcal{A} \subset \mathcal{M}$ be a diffuse abelian subalgebra. Then the following statements are equivalent:*

- (i) $\forall b \in \mathcal{M}^{sa}, E_{\mathcal{A}}(\overline{\mathcal{U}_{\mathcal{M}}(b)}) = \Omega_{\mathcal{A}}(b);$
- (ii) $\forall b \in \mathcal{M}^+, E_{\mathcal{A}}(\overline{\mathcal{C}_{\mathcal{M}}(b)}) = \Theta_{\mathcal{A}}(b) \cap \mathcal{A}^+.$

Proof. Using arguments similar to those in Lemma 3.3 we can prove that for $b \in \mathcal{M}^{\text{sa}}$, $E_{\mathcal{A}}(\overline{\mathcal{U}_{\mathcal{M}}(b)}) \subset \Omega_{\mathcal{A}}(b)$. If $b \in \mathcal{M}^+$, using the norm-continuity of $E_{\mathcal{A}}$ and Lemma 3.3,

$$E_{\mathcal{A}}(\overline{\mathcal{C}_{\mathcal{M}}(b)}) \subset \overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))} \subset \overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}} \subset \Theta_{\mathcal{A}}(b) \cap \mathcal{A}^+.$$

(i) \Rightarrow (ii). Let $a \in \Theta_{\mathcal{A}}(b) \cap \mathcal{A}^+$, $b \in \mathcal{M}^+$. Since \mathcal{A} is diffuse and abelian, by Proposition 2.3 there exists a spectral resolution of the identity $\{e(t)\}_{t \in [0,1]} \subseteq \mathcal{A}$ such that $\tau(e(t)) = t$ for $t \in [0,1]$ and such that $a = \int_0^1 \lambda_a(t) de(t)$. Consider the operator $b' = \int_0^1 \lambda_b(t) de(t)$. It is straightforward to verify that $\lambda_{b'} = \lambda_b$ so that, by Theorem 2.1, $\overline{\mathcal{U}_{\mathcal{M}}(b)} = \overline{\mathcal{U}_{\mathcal{M}}(b')}$. From this last fact it follows that $\overline{\mathcal{C}_{\mathcal{M}}(b)} = \overline{\mathcal{C}_{\mathcal{M}}(b')}$, and so after replacing b by b' we can assume that $b \in \mathcal{A}$. By Proposition 3.1 there exists $c \in \mathcal{A}^+$ such that $a \prec c \leq b$ and by hypothesis we get $a \in E_{\mathcal{A}}(\overline{\mathcal{U}_{\mathcal{M}}(c)})$. Again by Proposition 3.1, since $c \leq b$ implies $c \preceq b$, we get $c \in \overline{\mathcal{C}_{\mathcal{M}}(b)}$. Then $\mathcal{U}_{\mathcal{M}}(c) \subset \overline{\mathcal{C}_{\mathcal{M}}(b)}$, so we have $a \in E_{\mathcal{A}}(\overline{\mathcal{C}_{\mathcal{M}}(b)})$.

(ii) \Rightarrow (i). Let $b \in \mathcal{M}^{\text{sa}}$, $a \in \Omega_{\mathcal{A}}(b)$. Since $\lambda_{b+\alpha I} = \lambda_b + \alpha$, then $a \prec b$ if and only if $a + \alpha \prec b + \alpha$. Hence, $\Omega_{\mathcal{A}}(b + \alpha I) = \Omega_{\mathcal{A}}(b) + \alpha I$, and it is clear that $E_{\mathcal{A}}(\overline{\mathcal{U}_{\mathcal{M}}(b + \alpha I)}) = E_{\mathcal{A}}(\overline{\mathcal{U}_{\mathcal{M}}(b)}) + \alpha I$. Thus, we can assume without loss of generality that $a, b \in \mathcal{M}^+$. The following argument was inspired by the proof of Theorem 4.1 in [5]. Since in particular $a \in \Theta_{\mathcal{A}}(b) \cap \mathcal{A}^+$, by hypothesis there exist $c \in \mathcal{M}^+$ and a sequence $(v_n)_{n \in \mathbb{N}} \subset \mathcal{M}$ with $\|v_n\| \leq 1$, $n \in \mathbb{N}$, such that

$$(10) \quad \lim_{n \rightarrow \infty} \|v_n^* b v_n - c\| = 0 \quad \text{and} \quad E_{\mathcal{A}}(c) = a.$$

So $\tau(c) = \tau(a) = \tau(b)$. Let $p = p^b(0, \|b\|)$.

Claim. $\lim_{n \rightarrow \infty} \|p - |v_n^* p|\|_1 = 0$.

Since \mathcal{M} is a finite factor, the partial isometry in the polar decomposition of $v_n^* p$ can be extended to a unitary u_n : so $v_n^* p = u_n |v_n^* p|$. Thus

$$\begin{aligned} \|v_n^* b v_n - u_n b u_n^*\|_1 &= \|v_n^* p b (v_n^* p)^* - u_n b u_n^*\|_1 \\ &= \|u_n |v_n^* p| b |v_n^* p| u_n^* - u_n b u_n^*\|_1 \\ &= \| |v_n^* p| b |p v_n^*| - b \|_1 \\ &\leq \|(|v_n^* p| - p) b |v_n^* p|\|_1 + \|b (|v_n^* p| - p)\|_1 \\ &\leq \| |v_n^* p| - p \|_1 \|b |v_n^* p|\|_1 + \|b\| \| |v_n^* p| - p \|_1 \\ &\leq 2 \|b\| \| |v_n^* p| - p \|_1 \xrightarrow{n} 0. \end{aligned}$$

By (10) and the inequalities above, $\lim_n \|c - u_n b u_n^*\|_1 = 0$, and so $c \in \overline{\mathcal{U}_{\mathcal{M}}(b)}^{\sigma\text{-sot}}$. Using Theorem 2.1,

$$a = E_{\mathcal{A}}(c) \in E_{\mathcal{A}}(\overline{\mathcal{U}_{\mathcal{M}}(b)}^{\sigma\text{-sot}}) = E_{\mathcal{A}}(\overline{\mathcal{U}_{\mathcal{M}}(b)}).$$

Proof of the claim: Since $\|v_n\| \leq 1$, $p v_n v_n^* p \leq p$, and so $|v_n^* p| \leq p$. Then by (10),

$$\begin{aligned} 0 &\leq \lim_n \tau((1 - v_n v_n^*)b) = \lim_n \tau(b - v_n^* b v_n) \\ &= \lim_n \tau(c - v_n^* b v_n) \leq \lim_n \|c - v_n^* b v_n\| = 0. \end{aligned}$$

Let $\varepsilon > 0$. Since $b(b + \delta)^{-1} \nearrow p$ strongly when $\delta \rightarrow 0$ and

$$0 \leq \tau((1 - v_n v_n^*)(p - b(b + \delta)^{-1})) \leq \tau(p - b(b + \delta)^{-1}),$$

we can choose δ such that $\tau((1 - v_n v_n^*)p) \leq \varepsilon + \tau((1 - v_n v_n^*)b(b + \delta)^{-1})$ for every $n \in \mathbb{N}$. Then, choosing n such that $\tau((1 - v_n v_n^*)b) \leq \|(b + \delta)^{-1}\|^{-1} \varepsilon$, we obtain

$$\begin{aligned} 0 &\leq \tau((1 - v_n v_n^*)p) \leq \varepsilon + \tau((1 - v_n v_n^*)b(b + \delta)^{-1}) \\ &= \varepsilon + \tau((1 - v_n v_n^*)^{1/2} b^{1/2} (b + \delta)^{-1} b^{1/2} (1 - v_n v_n^*)^{1/2}) \\ &\leq \varepsilon + \|(b + \delta)^{-1}\| \tau((1 - v_n v_n^*)b) \leq 2\varepsilon. \end{aligned}$$

Therefore $\lim_n \tau((1 - v_n v_n^*)p) = 0$. For any $x \in \mathcal{M}^+$ with $\|x\| \leq 1$, $x - x^2 = x(1 - x) = x^{1/2}(1 - x)x^{1/2} \geq 0$. Since $\|v_n^* p\| \leq 1$, we conclude that $|v_n^* p|^2 \leq |v_n^* p|$, and so

$$\begin{aligned} \|p - |v_n^* p|\|_1 &= \tau(p - |v_n^* p|) \leq \tau(p - |v_n^* p|^2) \\ &= \tau(p - p v_n v_n^* p) = \tau((1 - v_n v_n^*)p) \rightarrow 0. \quad \square \end{aligned}$$

We finish with the following remark concerning the relation between our main result and the problem (9). The characterization in Theorem 3.4 of the positive operators in a diffuse abelian subalgebra \mathcal{A} majorized by a fixed $b \in \mathcal{M}^+$ is weaker than that posed in (9), since in general (using Corollary 3.2)

$$(11) \quad E_{\mathcal{A}}(\overline{\mathcal{C}_{\mathcal{M}}(b)}) = E_{\mathcal{A}}(\overline{\mathcal{C}_{\mathcal{M}}(b)})^{\sigma\text{-sot}} \subset \overline{E_{\mathcal{A}}(\mathcal{C}_{\mathcal{M}}(b))}^{\sigma\text{-sot}}.$$

By Theorems 3.4 and 4.1, an affirmative answer to the Arveson-Kadison problem would imply equality in (11) and, conversely, equality in (11) would settle the Arveson-Kadison problem affirmatively.

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