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SPACES OF REPRESENTATIONS AND ENVELOPING L.M.C. *-ALGEBRAS

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Given a l.m.c. *-algebra E with a b.a.i., the space of representations $\mathscr{R}(E)$ and the enveloping algebra $\mathscr{E}(E)$ of E are defined. Under a suitable condition for the extreme points of E, $\mathscr{R}(E)$, $\mathscr{R}(\mathscr{E}(E))$ coincide topologically, a fact contributing to the openess of the map defining the topology of $\mathscr{R}(E)$. Furthermore, one gets $\mathscr{E}(E) = \varprojlim_{\alpha} \mathscr{E}(E_\alpha)$, within a topological algebraic isomorphism, where (E_α) is the inverse system of Banach algebras corresponding to E.

1. Introduction. There is a vast literature concerning representation theory of abstract Banach *-algebras (resp. C^*-algebras). On the other hand, due to recent considerations, it would be interesting and useful to have these results extended within the frame of (non-normed) topological *-algebras, a fact arising not only from the part of pure mathematics (e.g., function algebras), but also from that of applications in theoretical physics (:quantum mechanics).

The present paper provides within the context of l.m.c. *-algebras, extensions of various results referred to Banach *-algebras (resp. C^*-algebras) representation theory. More specifically, if E is a l.m.c. *-algebra with a b.a.i., $\mathscr{B}(E)$ will denote the non-zero extreme points of $\mathscr{P}(E)$ (:continuous positive linear forms on E), and $\mathscr{R}(E)$ the equivalence classes of all continuous topologically irreducible representations of E. The set $\mathscr{R}(E)$ endowed with the final topology τ_{δ_E} induced on it by the map $\delta_E: \mathscr{B}(E) \to \mathscr{R}(E)$ (:an extension of the classical "Gel' fand-Naimark-Segal map"; Th. 3.4) is called the *space of representations* of E. Thus, the paper is mainly concerned with the study of $\mathscr{R}(E)$ and the openess of the map δ_E. To this study, the notion of the *enveloping algebra* $\mathscr{E}(E)$ of E having by its definition the crucial C^*-property (Def. 4.1), plays an important role. Now, the openess of $\delta_{\mathscr{E}(E)}$, with E a bQ l.m.c. *-algebra with a b.a.i. (Def. 4.2) is obtained, leading thus to the required openess of δ_E (Th. 4.2), based besides on the fact that the spaces $\mathscr{B}(E)$, $\mathscr{R}(E)$ coincide topologically with the corresponding ones of $\mathscr{E}(E)$, when $\mathscr{B}(\mathscr{E}(E))$ is locally equicontinuous (Th. 4.1).

Furthermore, $\mathscr{E}(E/N(p_\alpha))$, $\mathscr{E}(E_\alpha)$ are isomorphic as topological algebras (Lemma 4.3) where $(E/N(p_\alpha))$, (E_α) are the inverse systems of normed respectively Banach algebras corresponding to E [1], a fact further applied to get an inverse limit decomposition of $\mathscr{E}(E)$ in terms of $(\mathscr{E}(E_\alpha))$ (Th. 4.3).

2. Preliminaries. We introduce in this section the notation and terminology applied throughout.

A *representation* ϕ (or a *-representation) of a *-algebra E is an involution preserving homomorphism of E into the C^*-algebra $\mathscr{L}(H_\varphi)$ of all bounded linear operators on some Hilbert space H_φ (:representation space of E).

A representation ϕ on a Hilbert space H_φ is *topologically irreducible* if H_φ, $\{0\}$ are the only closed linear subspaces of H_φ left invariant by $\phi(E)$. Moreover, ϕ is called *non-degenerate* if $\{\phi(x)(\xi): x \in E,\ \xi \in H_\varphi\}^- = H_\varphi$ where "$-$" means norm-closure. On the other hand, a vector $\xi \in H_\varphi$ is called *cyclic* for ϕ if $\{\phi(x)(\xi): x \in E\}^- = H_\varphi$; in that case ϕ is called cyclic. Now, the representations ϕ, ψ of E are *equivalent*, we write $\phi \sim \psi$ (cf. [7]), if there exists a Hilbert space isomorphism $U: H_\varphi \to H_\psi$ such that $\psi(x) \circ U = U \circ \phi(x)$, $x \in E$.

A *positive linear form* on a *-algebra E is a complex linear form f on E with $f(x^*x) \geqq 0$, $x \in E$. If E has an identity e, then we also suppose that $f(e) = 1$. The set of positive linear forms on E is denoted by $P(E)$. Now, if $f, g \in P(E)$ we write $f \geqq g$, and we say that f *bounds* g, if $f - g \geqq 0$. Thus, an element $f \in P(E)$ is an *extreme point* if $g \in P(E)$ and $f \geqq g$ implies $g = \lambda f$ with $\lambda \in [0, 1]$ (cf. also [7]).

A topological algebra E (:topological vector space with a separately continuous multiplication) is called *locally m-convex* (l.m.c.) if it has a local basis $\mathscr{U}$ consisting of m-barrels, (cf. [11] and [9; Chapt. 1, Th. 1.1]), where by an *m-barrel* we mean a subset of E which is closed, convex, balanced, absorbing and idempotent. We may always suppose that such a local basis is directed.

Given a l.m.c. algebra E with a directed local basis $\mathscr{U} = \{U_\alpha, \alpha \in A\}$, $\{p_\alpha, \alpha \in A\}$ will denote the family of submultiplicative semi-norms (:gauges) corresponding to $\mathscr{U}$. Then, $U_\alpha = \{x \in E: p_\alpha(x) \leqq 1\}$, $\alpha \in A$, [9; Chapt. 1, Lemma 2.3].

Now, by a l.m.c. **-algebra* we mean a l.m.c. algebra E with an involution * such that $p_\alpha(x^*) = p_\alpha(x)$, $\alpha \in A$, $x \in E$ (cf. also [5; p.p. 6, 7]). If moreover, $p_\alpha(x^*x) = p_\alpha(x)^2$, $\alpha \in A$, $x \in E$, E is called l.m.c. *C^*-algebra*. Note that if E is a l.m.c. algebra with an involution * such that $p_\alpha(x)^2 \leqq p_\alpha(x^*x)$, $\alpha \in A$, $x \in E$, E is a l.m.c. C^*-algebra. By a Fréchet l.m.c. *-algebra, we mean a l.m.c. *-algebra whose underlying locally convex space is Fréchet.

Furthermore, if $N(p_\alpha) = \ker(p_\alpha)$, $\alpha \in A$, $(E/N(p_\alpha))$, (E_α) denote the projective systems of normed and Banach *-algebras corresponding to E, where E_α is the completion of $E/N(p_\alpha)$, $\alpha \in A$ (cf. [1], [11]). The topology of E_α is defined by the norm $\dot{p}_\alpha$, with $\dot{p}_\alpha(x_\alpha) = p_\alpha(x)$, $x_\alpha = \pi_\alpha(x) = x + N(p_\alpha) \in E/N(p_\alpha)$, $\alpha \in A$, where π_α is the quotient map of E onto $E/N(p_\alpha)$. If E is a l.m.c. C^*-algebra, each E_α, $\alpha \in A$, is a C^*-algebra.

Now, E_1 will denote the respective unital l.m.c. *-algebra of E, with corresponding family of semi-norms (p_α^1) and involution* defined respectively by $p_\alpha^1(x, \lambda) = p_\alpha(x) + |\lambda|$, $(x, \lambda)^* = (x^*, \bar{\lambda})$, $(x, \lambda) \in E_1 = E \oplus \boldsymbol{C}$.

On the other hand, *a bounded approximate identity* (:b.α.i.) on E will be a net $(e_i)_{i \in I}$, with $p_\alpha(e_i) \leqq 1$, $\alpha \in A$, $i \in I$ and $\lim p_\alpha(e_i x - x) = 0 = \lim p_\alpha(x e_i - x)$, $x \in E$, $\alpha \in A$.

3. Space of representations of a l.m.c. *-algebra. Let E be a topological *-algebra (: *-algebra, which is also topological). Then, by a continuous representation of E we shall mean a *-morphism ϕ of E into $\mathscr{L}(H_\varphi)$, continuous relative to the uniform topology on $\mathscr{L}(H_\varphi)$. In the sequel, $R(E)$ (resp. $R'(E)$) will denote the set of all continuous (resp. continuous, topologically irreducible) representations of E. Note that "equivalence of representations" defines an equivalence relation "$\sim$" on $R(E)$ (and hence on $R'(E)$ too). In this respect, (ϕ, ϕ') in $R(E) \times R'(E)$ with $\phi \sim \phi'$ implies (ϕ, ϕ') in $R'(E) \times R'(E)$.

Now, set $\mathscr{R}(E) = R'(E)/\sim$, and denote by $[\phi]$ the respective class of $\phi \in R'(E)$ in $\mathscr{R}(E)$. In the rest of this section we work out the appropriate material for defining $\mathscr{R}(E)$ as a topological space.

Let E be a l.m.c. *-algebra, and E_s' its weak topological dual. Then, $E_s' = \bigcup_\alpha U_\alpha^0$, where U_α^0 is the polar of the neighborhood $U_\alpha = \{x \in E: p_\alpha(x) \leqq 1\}$, $\alpha \in A$. Thus, if $\mathscr{P}(E)$ denotes the set of all continuous positive linear forms on E, and $\mathscr{B}(E)$ the non-zero extreme points of $\mathscr{P}(E)$, we obtain

$$\mathscr{P}(E) = \bigcup_\alpha \mathscr{P}_\alpha(E), \ \mathscr{B}(E) = \bigcup_\alpha \mathscr{B}_\alpha(E) \tag{3.1}$$

with $\mathscr{P}_\alpha(E) = \{f \in \mathscr{P}(E): |f(x)| \leqq 1, \ x \in U_\alpha\}$ and $\mathscr{B}_\alpha(E)$ the extreme points of $\mathscr{P}_\alpha(E)$, $\alpha \in A$. The preceding sets being subsets of E_s' are considered endowed with the relative topology; moreover, since $\mathscr{P}_\alpha(E) = \mathscr{P}(E) \cap U_\alpha^0 \subset U_\alpha^0$, $\mathscr{P}_\alpha(E)$ (and therefore $\mathscr{B}_\alpha(E)$), $\alpha \in A$ is an equicontinuous subset of $\mathscr{P}(E)$.

Furthermore, note that a consequence of (3.1) and [9; Chapt. 1, Lemma 1.2] is that for each $f \in \mathscr{P}(E)$ there exists $\alpha \in A$ with $|f(x)| \leqq p_\alpha(x)$ for every $x \in E$. The next theorem extends an analogous result of [5; Th. 4.1].

THEOREM 3.1. *Let E be a* l.m.c. **-algebra. Then, for each $\alpha \in A$*

$$\mathscr{P}(E/N(p_\alpha)) = \mathscr{P}_\alpha(E) = \mathscr{P}(E_\alpha) ,$$

within homeomorphisms.

Proof. Let $\alpha \in A$ and $\mathscr{P}_\alpha(E)$ the corresponding subspace of $\mathscr{P}(E)$. Then, for each $f \in \mathscr{P}_\alpha(E)$, $N(p_\alpha) \subset N(f)$, so that we define $f_\alpha \in \mathscr{P}(E/N(p_\alpha))$ by $f_\alpha(x_\alpha) = f(x)$, $x_\alpha \in E/N(p_\alpha)$, and we denote its extension to E_α also by f_α. Thus, the map

$$\mathscr{P}_\alpha(E) \longrightarrow \mathscr{P}(E/N(p_\alpha))(\text{resp. } \mathscr{P}(E_\alpha)): f \longmapsto f_\alpha$$

is a homeomorphism, the continuity being a consequence of the equicontinuity of $\mathscr{P}(E_\alpha)$, since then the weak topologies $\sigma((E_\alpha)'_s, E/N(p_\alpha))$, $\sigma((E_\alpha)'_s, E_\alpha)$ coincide on $\mathscr{P}(E_\alpha)$, $\alpha \in A$ [3; p. 23, Prop. 5]. □

By Theorem 3.1 it is clear that $\mathscr{P}(E_\alpha)$ consists of all continuous positive linear forms on E_α with norm $\leqq 1$.

COROLLARY 3.1. *Let E be as in Theorem* 3.1. *Then, for each $\alpha \in A$*

$$\mathscr{B}(E/N(p_\alpha)) = \mathscr{B}_\alpha(E) = \mathscr{B}(E_\alpha) ,$$

within homeomorphisms. □

LEMMA 3.2. *Let E be a topological algebra with a* b.a.i. $(e_i)_{i \in I}$. *Then,*

(i) *If E has a continuous multiplication, $(e_i^2)_{i \in I}$ is a* b.a.i. *for E.*

(ii) *If E has a continuous involution *, $(e_i^*)_{i \in I}$ is a* b.a.i. *for E.*

(iii) *If in particular E is a* l.m.c. **-algebra, then $(e_\alpha^i)_{i \in I} = (e_i + N(p_\alpha))_{i \in I}$ $\alpha \in A$ is a* b.a.i. *for both $E/N(p_\alpha)$ and E_α, $\alpha \in A$.*

Proof. For (i) cf. [9; Chapt. 6, Lemma 11.1]. (ii) $(e_i^*)_{i \in I}$ is a bounded net in E, since * is continuous. Moreover, for each $x \in E$ $\lim (e_i^* x - x) = \lim (x^* e_i - x^*)^* = 0^* = 0$, and similarly $\lim (x e_i^*) = x$, $x \in E$. (iii) For each $\alpha \in A$ define $e_\alpha^i = \pi_\alpha(e_i) = e_i + N(p_\alpha)$, then $\dot{p}_\alpha(e_\alpha^i) = p_\alpha(e_i) \leqq 1$, $i \in I$, $\alpha \in A$. Furthermore, $\lim \dot{p}_\alpha(x_\alpha e_\alpha^i - x_\alpha) = \lim p_\alpha(x e_i - x) = 0$, $x_\alpha \in E/N(p_\alpha)$, $\alpha \in A$; by the same way $x_\alpha = \lim (e_\alpha^i x_\alpha)$, $x_\alpha \in E/N(p_\alpha)$, $\alpha \in A$. Hence, $(e_\alpha^i)_{i \in I}$ is a b.a.i. for $E/N(p_\alpha)$, $\alpha \in A$ while this net is also a b.a.i. for E_α, $\alpha \in A$ (ibid.). □

LEMMA 3.3. *Let E be a* l.m.c. **-algebra with a* b.a.i. $(e_i)_{i \in I}$, *and* $f \in \mathscr{P}(E)$. *Then,*

(i) $f(x^*) = \overline{f(x)}$, $x \in E$ (i.e., f *is real or hermitian*).

(ii) $|f(x)|^2 \leqq \|f_\alpha\| f(x^*x)$, $x \in E$.

Proof. (i) $f(x^*) = \lim_i f(x^*e_i) =$ [7; p. 27, (1)] $\lim_i \overline{f(e_i^*x)} = \overline{f(\lim_i e_i^*x)} =$ (Lemma 3.2, (ii)) $\overline{f(x)}$, $x \in E$.

(ii) $|f(x)|^2 =$ (Lemma 3.2, (ii)) $\lim_i |f(e_i^*x)|^2 \leqq$ [7; p. 27, (2)] $\lim_i f(e_i^*e_i)f(x^*x)$, $x \in E$. Now, if f_α is the element of $\mathscr{P}(E_\alpha)$ defined by f as in Theorem 3.1, $\lim_i f(e_i^*e_i) =$ (Lemma 3.2, (iii)) $\lim_i f_\alpha((e_\alpha^i)^*e_\alpha^i) =$ [7; Prop. 2.1.5, (v)] $\|f_\alpha\|$. Actually, $\|f_\alpha\| \leqq 1$, since $|f_\alpha(x_\alpha)| = |f(x)| \leqq 1$, $x \in U_\alpha$. □

The above assertion (i) is actually valid for any topological algebra with continuous involution and a not necessarily bounded a.i. Every element $f \in \mathscr{P}(E)$ satisfying conditions (i), (ii) of Lemma 3.3 is called *extendable.*

PROPOSITION 3.4. *Let E be a* l.m.c. **-algebra with a* b.a.i. $(e_i)_{i \in I}$. *Then,*

(i) *Each* $f \in \mathscr{P}(E)$ *is uniquely extended to an element* $f_1 \in \mathscr{P}(E_1)$ *with* $f_1(0, 1) = \|f_\alpha\|$, *where* $(0, 1)$ *denotes the identity element of* E_1.

(ii) *Each element of* $\mathscr{P}(E_1)$ *extending* f *bounds* f_1.

(iii) *If* $Q(E_1) = \{h \in \mathscr{P}(E_1): h(0, 1) = \|(h|_E)_\alpha\|\}$ *and an element of* $\mathscr{P}(E_1)$ *is bounded by an element of* $Q(E_1)$, *it must itself belong to* $Q(E_1)$.

(iv) $f \in \mathscr{B}(E) \Leftrightarrow f_1 \in \mathscr{B}(E_1) \Leftrightarrow \tilde{f}_1 \in \mathscr{B}(\tilde{E}_1)$, *where* $\tilde{E}_1$ *is the completion of* E_1 *and* $\tilde{f}_1$ *the extension of* f_1 *to* $\tilde{E}_1$.

Proof. (i) For each $f \in \mathscr{P}(E)$ define $f_1: E_1 \to C: (x, \lambda) \mapsto f_1(x, \lambda) = f(x) + \lambda \|f_\alpha\|$, where $f_\alpha \in \mathscr{P}(E_\alpha)$ (cf. Th. 3.1). Then, $f_1 \in P(E_1)$ with $f_1(0, 1) = \|f_\alpha\|$. Moreover, $|f_1(x, \lambda)| \leqq |f(x)| + |\lambda| \leqq p_\alpha(x) + |\lambda| = p_\alpha^1(x, \lambda)$, $(x, \lambda) \in E_1$, hence $f_1 \in \mathscr{P}(E_1)$.

(ii) Suppose that $g \in \mathscr{P}(E_1)$ extends $f \in \mathscr{P}(E)$. Then, there exists $\gamma \in A$ with $g \in \mathscr{P}_\gamma(E_1)$ and $f \in \mathscr{P}_\gamma(E)$, hence $\|g_\gamma\| \geqq \|f_\gamma\|$ which yields $g \geqq f_1$.

(iii) Let $g = h + k$ with $g \in Q(E_1)$ and $h, k \in \mathscr{P}(E_1)$. Then, $g \geqq h, k$ and $h + k = g = (g|_E)_1 = (h|_E)_1 + (k|_E)_1$. Moreover, $h(0, 1) \geqq (h|_E)_1(0, 1)$, $k(0, 1) \geqq (k|_E)_1(0, 1)$, which implies $h(0, 1) = (h|_E)_1(0, 1)$, $k(0, 1) = (k|_E)_1(0, 1)$, that is $h, k \in Q(E_1)$.

(iv) Let $f \in \mathscr{B}(E)$ and $g \in \mathscr{P}(E_1)$ with $f_1 \geqq g$. Then, $f \geqq g|_E$, i.e., $g|_E = \lambda f$, $\lambda \in [0, 1]$ and since $g(0, 1) = \lambda f_1(0, 1)$ by (iii), we conclude $g = \lambda f_1$, $\lambda \in [0, 1]$.

Conversely, let $f \in \mathscr{P}(E)$ with $f_1 \in \mathscr{B}(E_1)$ and $g \in \mathscr{P}(E)$ such that $f \geqq g$. Then, $f - g \in \mathscr{P}(E)$, so that $(f - g)_1 = f_1 - g_1 \in \mathscr{P}(E_1)$, i.e., $f_1 \geqq g_1$, $g_1 \in \mathscr{P}(E_1)$; but then, $g_1 = \lambda f_1$, $\lambda \in [0, 1]$, hence also $g = \lambda f$, $\lambda \in [0, 1]$. The second equivalence of (iv) is clear. □

REMARK 3.4. For E as in Proposition 3.4 and $\phi \in R(E)$ we define $\phi_1: E_1 \to \mathscr{L}(H_\varphi): (x, \lambda) \mapsto \phi_1(x, \lambda) = \phi(x) + \lambda id_{H_\varphi}$. Then, $\phi_1 \in R(E_1)$ and particularly $\phi \in R'(E) \Leftrightarrow \phi_1 \in R'(E_1) \Leftrightarrow \tilde{\phi}_1 \in R'(\tilde{E}_1)$, where $\tilde{\phi}_1$ is the extension of ϕ_1 to $\tilde{E}_1$.

Now, if f, $\tilde{f}_1$ are as in Proposition 3.4, $L_{\tilde{f}_1} = \{z \in \tilde{E}_1: \tilde{f}_1(z^*z) = 0\}$ is a left ideal of $\tilde{E}_1$ and $H_1 = \tilde{E}_1/L_{\tilde{f}_1}$ is a pre-Hilbert space with inner product $\langle z + L_{\tilde{f}_1}, w + L_{\tilde{f}_1}\rangle = \tilde{f}_1(w^*z)$, $w, z \in \tilde{E}_1$. Denote by H the respective Hilbert space, completion of H_1. Then, one obtains

$$\overline{E/L_{\tilde{f}_1}} = E_1/L_{\tilde{f}_1}$$

since $\|(e_i, 0) + L_{\tilde{f}_1} - (0, 1) + L_{\tilde{f}_1}\|^2 = f_1((e_i, -1)^*(e_i, -1)) = f(e_i^*e_i) - f(e_i) - \overline{f(e_i)} + \|f_\alpha\| \to 0$ (cf. proof of Lemma 3.3 and note that $\lim_i f(e_i) =$(Th. 3.1, Lemma 3.2) $\lim_i f_\alpha(e_\alpha^i) =$[7; Prop. 2.1.5, (v)] $\|f_\alpha\|$).

On the other hand,

$$\overline{E_1/L_{\tilde{f}_1}} = H_1 ,$$

hence one finally obtains

$$\overline{E/L_{\tilde{f}_1}} = H . \tag{3.2}$$

In this respect, the following extends [5; Th. 6.1], being actually the analogue in our case of the standard *Gel'fand-Naimark-Segal* construction.

THEOREM 3.4. *Let E be a* l.m.c. **-algebra with a* b.a.i., *and $f \in \mathscr{P}(E)$. Then, there exists a continuous representation ϕ_f of E and a cyclic vector ξ_f of ϕ_f such that $f(x) = \langle \phi_f(x)(\xi_f), \xi_f \rangle$, $x \in E$.*

Proof. For each $f \in \mathscr{P}(E)$, $\tilde{f}_1$ belongs to $\mathscr{P}(\tilde{E}_1)$ (Prop. 3.4), so that [5; Th. 6.1] there exists a continuous representation $\phi_{\tilde{f}_1}$ of $\tilde{E}_1$ into $\mathscr{L}(H)$ and a cyclic vector $\xi_{\tilde{f}_1}$ of $\phi_{\tilde{f}_1}$ in H such that

$$\tilde{f}_1(z) = \langle \phi_{\tilde{f}_1}(z)(\xi_{\tilde{f}_1}), \xi_{\tilde{f}_1} \rangle, \ z \in \tilde{E}_1 .$$

Thus, if $\phi_f = \phi_{\tilde{f}_1}|_E$ and $\xi_f = \xi_{\tilde{f}_1} \in H$, one obtains

$$f(x) = \langle \phi_f(x)(\xi_f), \xi_f \rangle, \ x \in E ,$$

where ξ_f is cyclic for ϕ_f as this follows by (3.2) and $\phi(E)(\xi_f) = E/L_{\tilde{f}_1}$. □

Now, given a l.m.c. *-algebra E let, for each $\alpha \in A$

$$(3.3) \qquad R_\alpha(E) = \{\phi \in R(E): \|\phi(x)\| \leqq kp_\alpha(x),\ x \in E\},\ k > 0\ ,$$

so that $R(E) = \bigcup_\alpha R_\alpha(E)$. Thus, we can define $\phi_\alpha \in R(E/N(p_\alpha))$ with $\phi_\alpha(x_\alpha) = \phi(x)$, $x_\alpha \in E/N(p_\alpha)$, so that if ϕ_α denotes also the extension of ϕ_α to E_α, one has $\|\phi_\alpha(z)\| \leqq \hat{p}_\alpha(z)$, $z \in E_\alpha$ [7; Prop. 1.3.7]; hence $\|\phi(x)\| \leqq p_\alpha(x)$, $x \in E$ in such a way that one may assume $k \leqq 1$ in (3.3), for each $\phi \in R_\alpha(E)$. Besides, if $R'_\alpha(E) = \{\phi \in R'(E): \phi \in R_\alpha(E)\}$ and $\mathscr{R}_\alpha(E) = R'_\alpha(E)/\sim$, we get

$$(3.4) \quad R(E) = \varinjlim_\alpha R_\alpha(E),\ R'(E) = \varinjlim_\alpha R'_\alpha(E,)\ \mathscr{R}(E) = \varinjlim_\alpha \mathscr{R}_\alpha(E)\ ,$$

within bijections [4; p. 92].

Now, if $\phi_\alpha \in R'(E_\alpha)$ and M is a closed linear subspace of $H_\varphi(=H_{\varphi_\alpha})$ with $\phi(E)(M) \subset M$, then $\phi_\alpha(E_\alpha)(M) \subset M$. Hence, $\phi \in R'_\alpha(E) \Leftrightarrow \phi_\alpha \in R'(E/N(p_\alpha))$ (resp. $R'(E_\alpha)$). Finally, notice that $\phi \sim \psi$ in $R'_\alpha(E)$ implies $\phi_\alpha \sim \psi_\alpha$ in $R'(E_\alpha)$. The above yields the following

PROPOSITION 3.5. *Let E be a* l.m.c. **-algebra. Then,*
(i) $R(E/N(p_\alpha)) = R_\alpha(E) = R(E_\alpha)$, $\alpha \in A$,
(ii) $R'(E/N(p_\alpha)) = R'_\alpha(E) = R'(E_\alpha)$, $\alpha \in A$,
(iii) $\mathscr{R}(E/N(p_\alpha)) = \mathscr{R}_\alpha(E) = \mathscr{R}(E_\alpha)$, $\alpha \in A$, *within bijections.* □

The following Banach *-algebras analogue [7; Prop. 2.5.4] extends also Corollary 6.4 of [5].

PROPOSITION 3.6. *Let E be a* l.m.c. **-algebra with a* b.a.i. *Let also $f \in \mathscr{P}(E)$ and ϕ_f the respective element of $R(E)$* (cf. Th. 3.4). *Then, $f \in \mathscr{B}(E) \Leftrightarrow \phi_f \in R'(E)$.*

Proof. $f \in \mathscr{B}(E)$ implies $\tilde{f}_1 \in \mathscr{B}(\tilde{E}_1)$ (Prop. 3.4, (iv)), so that [5; Cor. 6.4] $\phi_{\tilde{f}_1} \in R'(\tilde{E}_1)$, which implies $\phi_{f_1} = \phi_{\tilde{f}_1}|_{E_1} \in R'(E_1)$ and since $\phi_{f_1} = (\phi_f)_1$, $\phi_f \in R'(E)$ by Rem. 3.4.

Conversely, let $f \in \mathscr{P}(E)$ with $\phi_f \in R'(E)$. Then, $\phi_{f_1} = (\phi_f)_1 \in R'(E_1)$ (Remark 3.4), so that $\phi_{\tilde{f}_1} \in R'(\tilde{E}_1)$, which yields $\tilde{f}_1 \in \mathscr{B}(\tilde{E}_1)$ [5; Cor. 6.4]; hence $f \in \mathscr{B}(E)$ by Proposition 3.4, (iv). □

Furthermore, one gets the next (cf. also [7; Prop. 2.4.1, (ii)].

LEMMA 3.7. *Let E be a *-algebra and ϕ, ψ representations of E into $\mathscr{L}(H_\varphi)$, $\mathscr{L}(H_\psi)$ respectively. Let also ξ (resp. η) be a cyclic vector of ϕ (resp. ψ), with $\langle\phi(x)(\xi), \xi\rangle = \langle\psi(x)(\eta), \eta\rangle$, $x \in E$. Then, $\phi \sim \psi$ such that there exists a Hilbert space isomorphism $U: H_\varphi \to H_\psi$*

with $U \circ \phi(x) = \psi(x) \circ U$, $x \in E$ *and* $U(\xi) = \eta$. □

Now, regarding Proposition 3.6 we notice that for each $\phi \in R'(E)$ there exists $f \in \mathscr{B}(E)$ such that $\phi \sim \phi_f$: Indeed, if ξ is a cyclic vector of ϕ, the formula $f(x) = \langle \phi(x)(\xi), \xi \rangle$, $x \in E$ defines an element f of $\mathscr{P}(E)$. Hence, (Th. 3.4) there exists $\phi_f \in R(E)$ and a cyclic vector ξ_f of ϕ_f with $f(x) = \langle \phi_f(x)(\xi_f), \xi_f \rangle$, $x \in E$, so that (Lemma 3.7) $\phi \sim \phi_f$ in $R(E)$, i.e., $\phi_f \in R'(E)$, which by Proposition 3.6 implies $f \in \mathscr{B}(E)$. Hence, by Theorem 3.4 and Proposition 3.6 we now define an onto map

$$(3.5) \qquad \delta_E : \mathscr{B}(E) \longrightarrow \mathscr{R}(E) : f \longmapsto \delta_E(f) = [\phi_f] .$$

The set $\mathscr{R}(E)$ equipped with the final topology τ_{δ_E} induced on it by δ_E, is called the *space of representations* of E.

In the next § 4, under additional conditions for E we prove the openess of the map (3.5).

4. Enveloping algebra of a l.m.c. *-algebra. We define below the enveloping algebra $\mathscr{E}(E)$ of a l.m.c. *-algebra E with a b.a.i. It is proved that the representation theory of E is actually reduced to that of $\mathscr{E}(E)$ (Th. 4.1), the last algebra having the important "C^*-property", hence its significance for the latter theory. On the other hand, by further obtaining under appropriate conditions the openess of the map $\delta_{\mathscr{E}(E)}$, we finally get the same property for the map (3.5) (Th. 4.2). Further applications, concerning topological tensor product algebras, will be given elsewhere.

LEMMA 4.1. *Let E be a* l.m.c. **-algebra with a* a.b.i. *Then, for any $x \in E$ and $\alpha \in A$, the following hold true*:

(i) $a = b = c = d$, *where*

$$a = \sup \{\| \phi(x) \| : \phi \in R_\alpha(E)\}, \ b = \sup \{\| \phi(x) \| : \phi \in R'_\alpha(E)\} ,$$
$$c = (\sup \{f(x^*x) : f \in \mathscr{P}_\alpha(E)\})^{1/2}, \ d = (\sup \{f(x^*x) : f \in \mathscr{B}_\alpha(E)\})^{1/2} ,$$
$$x \in E .$$

(ii) *For each $\alpha \in A$, the map $r_\alpha : E \to \mathbf{R}^+ : x \mapsto r_\alpha(x) = d$, defines a submultiplicative semi-norm on E, which is *-preserving and has the C^*-property.*

Proof. The proof is an immediate consequence of [7; Prop. 2.7.1] since by Theorem 3.1, Corollary 3.1 and Proposition 3.5, one concludes that

$a = \sup\{\|\phi_\alpha(x_\alpha)\|: \phi_\alpha \in R(E_\alpha)\}$, $b = \sup\{\|\phi_\alpha(x_\alpha)\|: \phi_\alpha \in R'(E_\alpha)\}$,
$c = (\sup\{f_\alpha(x_\alpha^* x_\alpha): f_\alpha \in \mathscr{P}(E_\alpha)\})^{1/2}$, $d = (\sup\{f_\alpha(x_\alpha^* x_\alpha): f_\alpha \in \mathscr{B}(E_\alpha)\})^{1/2}$.

□

Regarding Lemma 4.1, note that b also coincides with

$$\sup\{\|\phi(x)\|: [\phi] \in \mathscr{R}_\alpha(E)\}\ .$$

Furthermore, since $\|\phi(x)\| \leqq p_\alpha(x)$, $x \in E$ for each $\phi \in R_\alpha(E)$, one obtains $r_\alpha(x) \leqq p_\alpha(x)$ for any $\alpha \in A$, $x \in E$, that is each $r_\alpha (\alpha \in A)$ is continuous with respect to the given topology of E.

DEFINITION 4.1. Let E be a l.m.c. *-algebra with a b.a.i., and $(E, (r_\alpha))$ the respective l.m.c. C^*-algebra defined by Lemma 4.1. Then, the "Hausdorff completion" of the latter, that is the algebra

$$\mathscr{E}(E) = \widetilde{(E, (r_\alpha))/I} \tag{4.1}$$

with $I = \cap\{N(r_\alpha): \alpha \in A\}$ a closed 2-sided self-adjoint ideal of E, is called the *enveloping algebra of* E.

In this regard, cf. also [6; p. 65] concerning Fréchet l.m.c. *-algebras with identity. It is clear that (4.1) provides a complete l.m.c. C^*-algebra, whose topology is defined by the family $(\tilde{q}_\alpha)$ of submultiplicative semi-norms, extensions of q_α, $\alpha \in A$ to $\mathscr{E}(E)$, where $q_\alpha(x + I) = \inf\{r_\alpha(x + i): i \in I\}$, $x + I \in (E, (r_\alpha))/I$. Moreover, if (e_j) is a b.a.i. for E, the net $(e_j + I)$ is a b.a.i. for $\mathscr{E}(E)$.

REMARK 4.1. A given l.m.c. *-algebra E with a b.a.i. has the C^*-property iff $r_\alpha = p_\alpha$ for each $\alpha \in A$, that is one has then $p_\alpha(x) \leqq r_\alpha(x)$, with $\alpha \in A$, $x \in E$: In fact, since E has the C^*-property, each E_α is a C^*-algebra, therefore E_α, $\alpha \in A$ has an isometric representation, say ϕ_α, that is $\|\phi_\alpha(z)\| = \dot{p}_\alpha(z)$, $z \in E_\alpha$ (cf. [7; Th. 2.6.1]). But then, $\|\phi(x)\| = p_\alpha(x)$, $x \in E$ with $\phi \in R_\alpha(E)$ (Prop. 3.5).

Now, it is clear that every complete l.m.c. C^*-algebra coincides with its enveloping algebra. In the sequel E/I will stand for $(E, (r_\alpha))/I$.

THEOREM 4.1. *Let E be a* l.m.c. *-algebra with a* b.a.i., *and $\mathscr{E}(E)$ its enveloping algebra with $\mathscr{B}(\mathscr{E}(E))$ locally equicontinuous. Then, $\mathscr{B}(E) = \mathscr{B}(\mathscr{E}(E))$ and $\mathscr{R}(E) = \mathscr{R}(\mathscr{E}(E))$ within homeomorphisms.*

Proof. If $f \in \mathscr{B}(E)$ there exists $\alpha \in A$ with $f \in \mathscr{B}_\alpha(E)$ and $|f(x)| \leqq r_\alpha(x)$, $x \in E$ (Lemma 3.3, (ii)). Thus, we define $g \in \mathscr{B}(E/I)$

with $g(x+I) = f(x)$, $x + I \in E/I$. Denoting also by g the respective element of $\mathscr{B}(\mathscr{E}(E))$ we have $g \in \mathscr{B}(\mathscr{E}(E)) \Leftrightarrow f \in \mathscr{B}(E)$. Now, the map $\Psi: \mathscr{B}(\mathscr{E}(E)) \to \mathscr{B}(E): g \mapsto \Psi(g) = f$ with $f = g \circ \tau$, where $\tau: E \to \mathscr{E}(E)$ is the canonical continuous morphism (Def. 4.1), is a continuous bijection. Moreover, the inverse of Ψ is certainly continuous for the weak topology induced on its range by E/I. On the other hand, let V be a neighborhood of g in $\mathscr{B}(\mathscr{E}(E))$ which we may always assume to be equicontinuous by hypothesis. Then, the weak topologies on V from E/I and $\widetilde{E/I} = \mathscr{E}(E)$ coincide [3; p. 23, Prop. 5], which proves the continuity of Ψ^{-1}.

Now, if $\phi \in R(E)$, there exists $\alpha \in A$ with $\phi \in R_\alpha(E)$ and $N(r_\alpha) \subset N(\phi)$, so that one gets $\phi' \in R(E/I)$ with $\phi'(x+I) = \phi(x)$, $x + I \in E/I$. Thus, preserving the same symbol for the extension of ϕ' to $\mathscr{E}(E)$ we have $\phi' \in R'(\mathscr{E}(E)) \Leftrightarrow \phi \in R'(E)$, so that the map $r: \mathscr{R}(\mathscr{E}(E)) \to \mathscr{R}(E)$: $[\phi'] \mapsto r([\phi']) = [\phi]$ with $\phi = \phi' \circ \tau$, is a homeomorphism as this follows by the relation $r \circ \delta_{\mathscr{E}(E)} = \delta_E \circ \Psi$, since δ_E, Ψ are continuous and $\mathscr{R}(\mathscr{E}(E))$ has the final topology induced on it by $\delta_{\mathscr{E}(E)}$, an analogous argument being valid for the inverse of r. □

Concerning the above theorem, we note that Ψ, r are always continuous bijections. Moreover, an element $\phi \in R(E)$ is non-degenerate iff the element $\phi' \in \mathscr{R}(\mathscr{E}(E))$ is non-degenerate, and for any $(\phi, \phi') \in R(E) \times R(\mathscr{E}(E))$ the set $\phi(E)$ is dense in $\phi'(\mathscr{E}(E))$.

Regarding the local equicontinuity of $\mathscr{B}(\mathscr{E}(E))$ we note that this, is equivalent with that of $\mathscr{B}(E)$ when for instance, $\mathscr{E}(E)$ is barrelled (cf., for example, [9; Chapt. III, Cor. 5.31]). In this respect (cf. also Def. 4.2 below as well as the comments following it.

Now, a topological algebra E is said to be a *Q-algebra*, if the set of its quasi-regular elements is open. If E is a Q-algebra, the same holds also true for its respective unital algebra E_1 [12; p. 174, I].

DEFINITION 4.2. A l.m.c. *-algebra E with a b.a.i., whose enveloping algebra $\mathscr{E}(E)$ is barrelled (l.m.c.) Q-algebra, is called a *bQ l.m.c. *-algebra.*

In case E is a Fréchet l.m.c. *-algebra, $\mathscr{E}(E)$ is by its definition Fréchet and thus barrelled. However, we still assume that $\mathscr{E}(E)$ is a Q-algebra to have the situation provided by Theorem 3 of [8], hence its application to the next result.

THEOREM 4.2. *Let E be a bQ l.m.c. *-algebra with a* b.a.i. *Then,*

$$\delta_E \colon \mathscr{B}(E) \longrightarrow \mathscr{R}(E)$$

is a (continuous) open map.

Proof. Clearly δ_E is continuous by the definition of the final topology τ_{δ_E} on $\mathscr{R}(E)$. Now, by [8; Th. 3] $\mathscr{E}(E)_1$ is a C^*-algebra (cf. also [13; Cor. 5]), and since $\mathscr{E}(E) \subset \mathscr{E}(E)_1$ ($\overrightarrow{\subset}$ means topological algebraic imbedding) $\mathscr{E}(E)$ becomes also a $\overrightarrow{C^*}$-algebra, so that $\mathscr{B}(\mathscr{E}(E))$ is equicontinuous, and $\delta_{\mathscr{E}(E)}$ open by [7; Th. 3.4.11]. Thus the assertion follows by Theorem 4.1 and the relation $\delta_E = r \circ \delta_{\mathscr{E}(E)} \circ \Psi^{-1}$. □

In the rest of this section we relate $\mathscr{E}(E)$ with the decomposition of E as an inverse limit of Banach algebras [1], [11]. Namely, we give $\mathscr{E}(E)$ (Th. 4.3) as an inverse limit of the C^*-algebras $\mathscr{E}(E_\alpha)$, $\alpha \in A$, which are the enveloping algebras of the Banach algebras E_α, $\alpha \in A$, corresponding to E. However, we still need the following.

LEMMA 4.3. *Let E be a* l.m.c. **-algebra with a* b.a.i. *Then,*

$$\mathscr{E}(E_\alpha) = \mathscr{E}(E/N(p_\alpha)) = (E/I)_\alpha = \mathscr{E}(E)_\alpha,\ \alpha \in A\ , \tag{4.2}$$

within topological algebraic isomorphisms.

Proof. By Definition 4.1 $\mathscr{E}(E/N(p_\alpha)) = \widetilde{(E/N(p_\alpha),\ t_\alpha)/I_\alpha}$ with $t_\alpha(x_\alpha) = \sup\{\|\phi_\alpha(x_\alpha)\| \colon \phi_\alpha \in R(E/N(p_\alpha))\} = r_\alpha(x)$, $x_\alpha \in E/N(p_\alpha)$, $\alpha \in A$ (cf. Prop. 3.5 and Lemma 4.1) and $I_\alpha = N(t_\alpha)$. Moreover, $t_\alpha \leqq \dot{p}_\alpha$, $\alpha \in A$, hence t_α has a unique extension $\tilde{t}_\alpha$ to E_α, $\alpha \in A$, so that if $\tilde{I}_\alpha = N(\tilde{t}_\alpha)$, $\mathscr{E}(E_\alpha) = \widetilde{(E_\alpha,\ \tilde{t}_\alpha)/\tilde{I}_\alpha}$, $\alpha \in A$. Now, for $F_\alpha = (E/N(p_\alpha),\ t_\alpha)/I_\alpha$ and $G_\alpha = (E_\alpha,\ \tilde{t}_\alpha)/\tilde{I}_\alpha$, $\alpha \in A$, consider the map

$$h_\alpha \colon F_\alpha \longrightarrow G_\alpha \colon x_\alpha + I_\alpha \longmapsto x_\alpha + \tilde{I}_\alpha,\ \alpha \in A\ ,$$

which is an algebraic isomorphism into. Then, if Q_α, $\tilde{Q}_\alpha$, $\alpha \in A$, are the norms defining the quotient topologies of F_α, G_α, $\alpha \in A$ respectively, one gets

$$Q_\alpha(x_\alpha + I_\alpha) = t_\alpha(x_\alpha) = \tilde{Q}_\alpha(x_\alpha + \tilde{I}_\alpha),\ x_\alpha \in E/N(p_\alpha),\ \alpha \in A\ ,$$

which yields h_α, $\alpha \in A$, as a topological isomorphism too. Now, since by $t_\alpha \leqq \dot{p}_\alpha$ Im (h_α) is dense in G_α, $\alpha \in A$, one obtains the first part of the assertion. The last part of the statement is similarly proved. Concerning the 2nd equality in (4.2), if $M_\alpha = (E/I)/N(q_\alpha)$, $\alpha \in A$, the map

$$k_\alpha \colon M_\alpha \longrightarrow F_\alpha \colon (x + I)_\alpha \longmapsto x_\alpha + I_\alpha,\ \alpha \in A\ ,$$

is an algebraic isomorphism. In fact, $k_\alpha, \alpha \in A$ is a topological isomorphism: Namely, $Q_\alpha(x_\alpha + I_\alpha) \leqq \dot{q}_\alpha((x + I)_\alpha)$, which yields the continuity of k_α. Besides, k_α^{-1} is continuous iff ρ: $(E/N(p_\alpha), t_\alpha) \to M_\alpha$: $x_\alpha \mapsto (x + I)_\alpha$ is continuous, which is true since $\dot{q}_\alpha(\rho(x_\alpha)) \leqq r_\alpha(x) = t_\alpha(x_\alpha)$, $x_\alpha \in E/N(p_\alpha)$, $(\alpha \in A)$. □

THEOREM 4.3. *If E is a* l.m.c. **-algebra with a* b.a.i., *and $\mathscr{E}(E)$ its enveloping algebra, then*

$$\mathscr{E}(E) = \lim_{\substack{\longleftarrow \\ \alpha}} \mathscr{E}(E_\alpha)\ ,$$

within an isomorphism of topological algebras.

Proof. $\mathscr{E}(E)$ is by its definition a complete l.m.c. C^*-algebra, hence

$$\mathscr{E}(E) = \lim_{\substack{\longleftarrow \\ \alpha}} \mathscr{E}(E)_\alpha \tag{4.3}$$

within a topological algebraic isomorphism, where $(\mathscr{E}(E)_\alpha)$ is the inverse system of C^*-algebras corresponding to $\mathscr{E}(E)$ [2], [11; Th. 5.1]. Now, (4.3) and Lemma 4.3 yield the assertion. □

Theorem 4.3 has a special bearing on a previous result in [6; Th. 4.3] referred to a Fréchet l.m.c. *-algebra with an identity. On the other hand, by applying categorical language, since $\mathscr{E}$ preserves continuous morphisms between l.m.c. *-algebras with b.a.i.'s (cf. also Th. 4.1) one may consider $\mathscr{E}$ as a *covariant functor* between the categories of the respective algebras E and $\mathscr{E}(E)$. Moreover, $\mathscr{E}$ is continuous (:preserves inverse limits) by Theorem 4.3 restricted to the full subcategory of Banach *-algebras.

The technique developed hitherto is further applied to the case of topological tensor products [10], by considering $\mathscr{E}(E \hat{\otimes}_\tau F)$ and $\mathscr{R}(E \hat{\otimes}_\tau F)$ with E, F suitable l.m.c. *-algebras and τ an "admissible" tensor product topology.

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REFERENCES

1. R. Arens, *A generalization of normed rings*, Pacific J. Math., **2** (1952), 455–471.
2. ———, *Dense inverse limit rings*, Michigan Math. J., **5** (1958), 169–182.

3. N. Bourbaki, *Espaces Vectoriels Topologiques*, Chap. III–V. Hermann Paris, 1967.
4. ———, *Théorie des Ensembles*, Chap. III. Hermann Paris, 1967.
5. R. M. Brooks, *On locally m-convex *-algebras*, Pacific J. Math., **23** (1967), 5–23.
6. ———, *On representing F^*-algebras*, Pacific J. Math., **39** (1971), 51–69.
7. J. Dixmier, *Les C^*-Algèbres et leurs Représentations*, Gauthier-Villars, Paris, 1964.
8. G. Lassner, *Über Realisierungen gewisser *-Algebren*, Math. Nachr., **52** (1972), 161–166.
9. A. Mallios, *General Theory of Topological Algebras*, Selected Topics, (book in preparation).
10. ———, *On the spectrum of a topological tensor product of locally convex algebras*, Math. Ann., **154** (1964), 171–180.
11. E. A. Michael, *Locally multiplicatively-convex topological algebras*, Mem. Amer. Math. Soc., No. 11 1952.
12. N. A. Naimark, *Normed Algebras*, Wolters-Noordhoff Publishing Groningen, 1970.
13. Z. Sebestyén, *Every C^*-seminorm is automatically submultiplicative*, Period. Math. Hung., **10** (1979), 1–8.

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