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NON-ARCHIMEDEAN EBERLEIN-ŠMULIAN THEORY

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ABSTRACT. It is shown that, for a large class of non-archimedean normed spaces $E$, a subset $X$ is weakly compact as soon as $f(X)$ is compact for all $f \in E'$ (Theorem 2.1), a fact that has no analogue in Functional Analysis over the real or complex numbers. As a Corollary we derive a non-archimedean version of the Eberlein-Šmulian Theorem (2.2 and 2.3, for the 'classical' theorem, see [1], VIII, §2 Theorem 1 and Corollary, page 219).

KEY WORDS AND PHRASES. Non-archimedean Banach space, weak compactness.

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INTRODUCTION

Let $E$ be a two-dimensional normed space over $\mathbb{R}$ or $\mathbb{C}$ and let $X := \{x \in E : 0 < \|x\| \leq 1\}$. Each $f \in E'$ has zeros on $X$, so $f(X) = f(\{0\} \cup X)$ is compact, while obviously $X$ is not. The same story can be told when we replace $\mathbb{R}$ or $\mathbb{C}$ by a complete non-trivially valued non-archimedean field $K$ that is locally compact. However, if $K$ is not locally compact then, under reasonable conditions, for a subset $X$ of a normed space $E$ over $K$ compactness of $f(X)$ for all $f \in E'$ implies weak compactness of $X$ (we point out that if such an $X$ has more than one point it cannot be convex). To prove this curious fact (in §2) we shall develop some machinery in §1.

PRELIMINARIES

Throughout $K$ is a non-trivially non-archimedean valued field which is complete with respect to the metric induced by the valuation $|\ |$, and $E$ is a normed $K$-vector space, where we assume $\|\|$ to satisfy the strong triangle inequality $\|x + y\| \leq \max(\|x\|, \|y\|)$. We write $|K^*| := \{|\lambda| : \lambda \in K, \lambda \neq 0\}$, $B_E(0,r) := \{x \in E : \|x\| \leq r\}$, $B_E := B_E(0,1)$.

$E'$ is the space of all linear continuous functions $E \to K$. Equipped with the norm $f \mapsto \sup\{|f(x)| : x \in B_E\}$ it is a Banach space (i.e. a complete normed space). $E$ is called normpolar if the norm is polar i.e. if $\|\| = \sup\{|f(x)| : f \in E', |f| \leq \|\|\}$ (i.e. polarization), in other words, if $\gamma : E \to E''$ is an isometry. $E'$ is always normpolar. We assume throughout this note that $E$ is normpolar.

A subset $A$ of a (normed) space $E$ is absolutely convex if it is a module over $B_K$. A set $X \subset E$ is convex if it is either empty or an additive coset of an absolutely convex set. A subset $A$ of $E$ is called edged if it is absolutely convex and, in case the valuation of $K$ is dense, $A = \bigcap\{\lambda A : \lambda \in K, |\lambda| > 1\}$. The weak topology $w = \sigma(E,E')$ is the weakest topology on $E$ making all $f \in E'$ continuous. The weak-star topology $w' = \sigma(E',E)$ is the weakest topology.
on $E'$ making all evaluation maps $f \mapsto f(a)$ ($a \in E$) continuous. For $X \subset E'$ we denote its $w'$-closure by $X^w$.

For other notions used in this paper we refer to [4].

1. SEPARATION OF $w'$-PRECOMPACT SETS

LEMMA 1.1. Let $X$ be a bounded subset of $E'$. Then $\{x \in E : \inf_{f \in X} |f(x)| > 0\}$ is open in $E$.

Proof. $X$ is equicontinuous, so for each $n \in \mathbb{N}$ the set $U_n := \{x \in E : |f(x)| > \frac{1}{n} \text{ for all } f \in X\}$ is open. Then so is $\bigcup_n U_n = \{x \in E : \inf_{f \in X} |f(x)| > 0\}$.

LEMMA 1.2. Let $K$ be not locally compact. Let $X \subset E'$ and $a \in E$ be such that $X(a) := \{f(a) : f \in X\}$ is precompact. Suppose $X \subset g + U$ where $U$ is an edged zero neighbourhood in $E'$, $U$ $w'$-closed and where $g \in E' \setminus U$. Then for any $\varepsilon > 0$ there exists $a \in E$ for which $\|a - b\| \leq \varepsilon$ and $\inf_{f \in X} |f(b) - f(a)| > 0$.

Proof. There exists an $r \in [K^*]$ such that $B_{E'}(0, r) \subset U$. Choose $\delta \in K$, $0 < |\delta| < 1$. The equivalence relation $\sim$ on $K^*$ given by $\alpha \sim \beta$ iff $|\alpha - \beta| < |\beta|$ yields an open partition of $C := \{\lambda \in K : |\delta r e| = |\lambda| \leq r\}$ that is infinite because $K$ is not locally compact. By precompactness $X(a)$ cannot meet each equivalence class and there exists a $\gamma \in C$ such that

\[(*) \quad |f(a) - \gamma| \geq |\gamma| \quad (f \in X).
\]

$U$ is $w'$-closed and edged, $g \notin U$, so by [6], 4.8 there exists a $c \in E$ such that $g(c) = \gamma$, $|f(c)| < |\gamma|$ for all $f \in U$. Set $b := a - c$. We have $|f(c)| \leq |\gamma|$ for all $f \in B_{E'}(0, r)$ so $\|a - b\| = \|a - c\| \leq |\gamma| r^{-1} \leq \varepsilon$. For each $f \in X$, writing $f = g + u$ where $u \in U$, we obtain $|f(c) - \gamma| = |f(c) - g(c)| = |u(c)| < |\gamma|$. This, combined with $(*)$, yields $|f(a) - \gamma| > |f(c) - \gamma|$ for all $f \in X$, so $|f(b)| = |f(a) - f(c)| = \max(|f(a) - \gamma|, |f(c) - \gamma|) = |f(a) - \gamma| \geq |\gamma|$. It follows that $\inf_{f \in X} |f(b)| > 0$.

COROLLARY 1.3. Let $K$ be not locally compact, let $E$ be a Banach space. Let $X \subset E'$ be $w'$-precompact. Suppose $X \subset g + U$ where $U$ is an edged zero neighbourhood in $E'$, $U$ $w'$-closed, $g \in E' \setminus U$. Then $\{x \in E : \inf_{f \in X} |f(x)| > 0\}$ is open and dense in $E$.

Proof. Just combine Lemmas 1.1 ($w'$-precompactness implies $w'$-boundedness hence norm boundedness by completeness) and 1.2.

DEFINITION 1.4. Let us call $X \subset E'$ $\sigma$-decomposable in $E'$ if for each $g \in E' \setminus X$ there exist $f_1, f_2, \ldots \in E'$ and edged zero neighbourhoods $U_1, U_2, \ldots$ in $E'$ such that each $U_n$ is $w'$-closed and $X \subset \bigcup_{n} (f_n + U_n)$.

THEOREM 1.5. (SEPARATION THEOREM) Let $K$ be not locally compact, let $E$ be a Banach space, let $X \subset E'$ be $w'$-precompact and $\sigma$-decomposable in $E'$. Then for each $g \in E' \setminus X$ there exists an $a \in E$ such that $g(a) \neq f(a)$ for all $f \in X$.

Proof. Without loss, assume $g = 0$. Let $\{f_n + U_n : n \in \mathbb{N}\}$ be a covering of $X$ like in Definition 1.4. By Corollary 1.3 for each $n \in \mathbb{N}$ the set $\{x \in E : \inf_{f \in X_n} |f(x)| > 0\}$ is open and dense in $E$, where $X_n := X \cap (f_n + U_n)$. By completeness and the Baire Category Theorem $\{x \in E : f(x) \neq 0 \text{ for all } f \in X\} \supset \bigcap_{n} \{x \in E : \inf_{f \in X_n} |f(x)| > 0\} \neq \emptyset$.

REMARK. It is not hard, by modifying 1.1 - 1.5, to prove the following dual form of this separation theorem. Let $K$ be not locally compact, let $X \subset E$ be weakly precompact and $\sigma$-decomposable in $E$ (see below). Then for each $a \in E \setminus X$ there exists an $f \in E'$ such that $f(a) \neq f(X)$. Here, $X$ is called $\sigma$-decomposable in $E$ if for each $a \in E \setminus X$ there exist $x_1, x_2, \ldots \in X$ and edged zero neighbourhoods $U_1, U_2, \ldots$ in $E$ such that each $U_n$ is weakly closed and $X \subset \bigcup_{n} (x_n + U_n)$, $a \notin \bigcup_{n} (x_n + U_n)$.
COROLLARY 1.6. Let $K$ be not locally compact, let $E$ be a Banach space, let $X \subset E'$ be $\sigma$-decomposable in $E'$. Suppose $X(a) := \{ f(a) : f \in X \}$ is compact for all $a \in E$. Then $X$ is $w'$-compact.

Proof. The map $f \mapsto (f(a))_{a \in E}$ is a homeomorphism of $(E', w')$ onto a subspace of $K^E$. The image of $X$ lies in the compact subset $\prod_{a \in E} X(a)$ so $X$ is $w'$-precompact. Since $E'$ is $w'$-quasiconnected by the $p$-adic Alaoglu Theorem [8], 3.1, it suffices to show that $X$ is $w'$-closed. To this end, let $g \in E' \setminus X$. By Theorem 1.5 there exists an $a \in E$ such that $g(a) \not\in X(a)$. Now $X(a) \subset \overline{X}(a)_w \subset X(a)$, so $g(a) \not\in \overline{X}(a)$ i.e. $g \not\in \overline{X}(a)$.

To find examples of $\sigma$-decomposable sets (in 1.9-1.11) we need the following Lemmas.

LEMMA 1.7. Let $n \in \mathbb{N}$, let $D$ be an $n$-dimensional subspace of $E'$. Then for each $t \in (0, 1)$ there exist $a_1, a_2, \ldots, a_n \in B_E$ such that $\max_{1 \leq i \leq n} |f(a_i)| \geq t||f||$ $(f \in D)$.

Proof. First assume that the valuation of $K$ is dense. The space $H := \{ x \in E : f(x) = 0 \text{ for all } f \in D \}$ has codimension $n$ in $E$. Choose $s \in (t, 1)$ and let $g_1, \ldots, g_n$ be a $\sqrt{s}$-orthogonal base of $(E/H)'$ such that $s^{-1} \leq ||g_i|| \leq t^{-1}$ for $i \in \{1, \ldots, n\}$. There exist $b_1, \ldots, b_n \in E/H$ such that $g_i(b_j) = \delta_{ij}$, $i, j \in \{1, \ldots, n\}$. Let $s \in \{1, \ldots, n\}$, let $g = \Sigma \lambda_i g_i \in (E/H)'$. Then $||g|| \geq \sqrt{s} \max \lambda_i ||g_i||$ and $||g(b_i)|| = \lambda_i s \max \lambda_j ||g_j|| \geq \lambda_i \Sigma \lambda_i ||g_i|| = t||g|| = t||f||$. So $||b_i|| < 1$. Thus, with $\pi : E \to E/H$ denoting the canonical quotient map, there exist $a_1, \ldots, a_n \in E$ with $||a_i|| = ||b_i||$ and $\pi(a_i) = b_i$ for each $i$. The adjoint $\pi'$ of $\pi$ maps $(E/H)'$ isometrically onto $D$. Now let $f \in D$. Then $f = \pi'(g)$ where $g \in (E/H)'$, $||g|| = ||f||$. We have, writing $g = \sum_{i=1}^n \lambda_i \lambda_i \max_{1 \leq i \leq n} |f(a_i)| = \max |g(b_i)| = \max |\lambda_i| \geq t \max |\lambda_i| ||g|| \geq t||\Sigma \lambda_i g_i|| = t||g|| = t||f||$.

Now, if the valuation is discrete we can modify the above proof by taking $s = t = 1$. Then the $b_i$ have norm $\leq 1$ (rather than $< 1$), but one can use that $E/H$ is a strict quotient i.e. there exist $a_1, \ldots, a_n \in E$ such that $a_i \in \overline{X}$ with $a_i \in \overline{X}$ and $\pi(a_i) = b_i$ for each $i$.

LEMMA 1.8. Let $D$ be a subspace of $E'$, $D$ of countable type. Then there is a sequence $a_1, a_2, \ldots \in B_E$ such that $||f|| = \sup_{a \in E} |f(a)|$ for all $f \in D$.

Proof. Let $D_1 \subset D_2 \subset \ldots$ be finite-dimensional subspaces of $D$, $\bigcup D_n$ is dense in $D$. Let $t \in (0, 1)$. By Lemma 1.7 there exists a finite set $F_n \subset B_E$ such that $\max_{a \in E} |f(a)| \geq t||f||$ for all $f \in D_n$.

So, for $F^1 := \bigcup_{n \in \mathbb{N}} F_n$, we obtain

\begin{equation}
\tag{*}
||f|| \geq \sup_{a \in E} |f(a)| \geq t||f|| \quad (f \in \bigcup_{n \in \mathbb{N}} D_n).
\end{equation}

Now $F := \bigcup_{n \in \mathbb{Q}(0, 1)} F^1$ is countable and $(*)$ implies $||f|| = \sup_{a \in E} |f(a)|$ for all $f \in \bigcup_{n \in \mathbb{N}} D_n$, hence, by continuity, for all $f \in D$.

PROPOSITION 1.9. Let $X \subset E'$ be such that $X(a) := \{ f(a) : f \in X \}$ is separable for each $a \in E$ and $|X|$ is of countable type. Then $X$ is $\sigma$-decomposable in $E'$.

Proof. Let $g \in E' \setminus X$. Then $D := \{ g \} \cup X$ is of countable type so by Lemma 1.8 there exist $a_1, a_2, \ldots \in B_E$ such that

\begin{equation}
\tag{**}
||h|| = \sup_{a \in E} |h(a)| \quad (h \in D).
\end{equation}

For each $m, n \in \mathbb{N}$ the set $U_{mn} := \{ h \in E' : |h(a_n)| \leq 1/m \}$ is an edged $w'$-zero neighbourhood. Its cosets, except for $g + U_{mn}$, cover $X \setminus (g + U_{mn})$ and by separability of $X(a_n)$ there exists a countable subcovering $F_{mn}$ no member of which contains $g$. Then $\bigcup_{m, n} F_{mn}$ still avoids $g$; it remains to be shown that it covers $X$. Suppose $f \in X$ is not covered. Then $f \not\in g + U_{mn}$ for all
m, n so $|f(a_n) - g(a_n)| = 0$ for all n. Now $f - g \in D$, so by (*) we obtain $\|f - g\| = 0$ i.e. $f = g$, a contradiction since $g \notin X$.

**COROLLARY 1.10.** Let $X \subset E'$. If $X$ is norm precompact, or $X$ is $w'$-precompact and $|X|$ is of countable type, then $X$ is $\sigma$-decomposable in $E'$.

**PROPOSITION 1.11.** Let $X \subset E'$ be such that $X(a)$ is separable for each $a \in E$. Suppose that for each $h \in \overline{X}'$ the set $X \cup \{h\}$ is $w'$-metrizable. Then $X$ is $\sigma$-decomposable in $E'$.

**Proof.** Let $g \in E' \setminus X$. If $g \notin \overline{X}'$ then there exists a $w'$-zero neighbourhood $U$ such that $(g + U) \cap X = \emptyset$. We may assume that $U$ is of the form $\{f \in E' : |f(a_1)| \leq \varepsilon, \ldots, |f(a_n)| \leq \varepsilon\}$ for some $\varepsilon > 0$, $n \in \mathbb{N}$, $a_1, \ldots, a_n \in E$. Then $U$ is $w'$-closed and edged. By separability of $X(a_1) \times \ldots \times X(a_n)$ only countably many of the cosets $f + U : f \in X$ cover $X$ and none of them contains $g$. Now let $g \in \overline{X}'$. By $w'$-metrizability there exist $w'$-neighbourhoods of zero $U_1 \supset U_2 \supset \ldots$ such that $X \cap (g + U_n) = \emptyset$. We may suppose that the $U_n$ are $w'$-closed and edged. By separability, like above, for each $n$ the set $X \setminus (g + U_n)$ is covered by countably many additive cosets of $U_n$ none of them containing $g$. Their union is a countable covering of $X$ avoiding $g$.

2. **EBERLEIN-ŠMULIAN THEORY**

We now apply the theory of §1. Recall ([5], p. 57) that $E$ is said to have property $(\ast)$ if for each subspace $D$ of countable type, every $f \in D'$ has an extension $\overline{f} \in E'$. By the non-archimedean Hahn-Banach Theorem [4], 4.8 every normed space over a spherically complete $K$ has $(\ast)$. For general $K$, spaces with a base, in particular spaces of countable type, have $(\ast)$ ([5], p. 58), and so have strongly polar spaces ([6], 4.2). Recall that $E$ is assumed to be normpolar.

**THEOREM 2.1.** Let $K$ be not locally compact, let $X$ be a subset of $E$ such that $f(X)$ is compact for all $f \in E'$. Then each one of the following properties implies that $X$ is weakly compact and weakly metrizable.

(i) $E$ has property $(\ast)$.

(ii) $E'$ is of countable type.

(iii) $|X|$ is of countable type.

Moreover, in case (i) $X$ is norm compact and the weak and norm topology coincide on $X$.

**Proof.** The natural isometry $j : E \to E''$ is easily seen to be a homeomorphism of $E$ with the weak topology onto $j(E)$ with the restriction of the $w'$-topology $\sigma(E'', E')$. We show that $j(X)$ is $\sigma$-decomposable in $E''$. First note that the predual $E'$ is normpolar. In case (i), from weak precompactness of $X$ it follows that $X$ is norm precompact by [7], Th. 3 (the assumption made throughout [7] that $E$ is complete is easily seen to be superfluous here). So $j(X)$ is norm precompact in $E''$ and therefore $\sigma$-decomposable by Corollary 1.10. For case (ii) observe that every $(w'')$-bounded subset of $E''$ is $w'$-metrizable ([8], 6.1) which applies to $j(X) \cup \{\emptyset\}$ for any $\emptyset \in E''$. For each $f \in E'$ the set $j(X)(f) = f(X)$ is compact hence separable so $j(X)$ is $\sigma$-decomposable in $E''$ by Proposition 1.11. For case (iii) we can directly apply Corollary 1.10. Thus, $j(X)$ is $\sigma$-decomposable, and from Corollary 1.6 we conclude that $j(X)$ is $w'$-compact, so $X = j^{-1}(j(X))$ is $w'$-compact. Observe that $X$ is $w'$-bounded hence bounded by normpolarity ([6], 7.7).

We have seen in passing that $j(X)$ is $w'$-metrizable in case (ii), so $X$ is weakly metrizable. Now let $X$ satisfy (iii). Then $[j(X)]$ is of countable type so by Lemma 1.8 there exist $f_1, f_2, \ldots \in B_{E'}$ such that $\|[j(x)]\| = \sup\{|f_n(x)| : n \in \mathbb{N}\}$ for all $x \in X$. The formula $d(x, y) = \sup\{|f_n(x) - f_n(y)| : n \in \mathbb{N}\}$ defines an ultrametric on $X$ (if $d(x, y) = 0$ then $|f_n(x) - f_n(y)| = 0$ for all $n$ so $\|x - y\| = 0$). By boundedness of $X$ the induced topology is weaker than the weak topology on $X$, but by
weak compactness these topologies coincide and so \( X \) is weakly metrizable. Finally, in case (i) apply \([6], 5.12\) to conclude that on \( X \) the weak and norm topology coincide, and that therefore \( X \) is norm compact and \( w \)-metrizable.

**Remarks.**

1. If \( K \) is not spherically complete the space \( \ell^\infty \) does not have property \((\ast)\) \([4], 4.15\) \((\delta) \Rightarrow (\gamma)\)
   but since \( (\ell^\infty)' \simeq c_0 \) \([4], 4.17\) it satisfies (ii) of the above Theorem, and so do the non-reflexive space \( \ell^\infty \oplus \ell^\infty \) \((3), 2.3\) and the space \( D \) of \([4], 4.1\).

2. Let \( K \) be not spherically complete, let \( E := \ell^\infty \), let \( X := \{0\} \cup \{e_1, e_2, \ldots\} \subset \ell^\infty \), when \( e_1, e_2, \ldots \) are the unit vectors. Then (ii) and (iii) above hold. \( X \) is weakly compact (since \( \lim e_n = 0 \) weakly) but is obviously not norm compact.

3. The following example indicates that extending Theorem 2.1 to, say, metrizable locally convex spaces is doubtful. Let \( E := K^N \) with the product topology. Then \( E' \cong \bigoplus_N K \). Let \( X := \{e_1, e_2, \ldots\} \) where \( e_1, e_2, \ldots \) are the unit vectors of \( K^N \). Then \( E \) is of countable type so (i), (ii), (iii) of Theorem 2.1 are (formally) satisfied. For each \( f \in E' \) we have \( f(e_n) = 0 \) for large \( n \), so \( f(X) \) is finite (hence compact) and contains 0. Yet, \( X \) is not (weakly) compact as \( 0 = \lim_{n \to \infty} e_n \notin X \).

The following is now an almost trivial consequence of Theorem 2.1.

**Corollary 2.2.** \((p\text{-adic Eberlein-Smulian Theorem I})\) Let \( K \) be not locally compact and let \( X, E \) satisfy one of the conditions (i), (ii), (iii) of Theorem 2.1. Then the following are equivalent.

\[(a) \quad X \text{ is weakly compact.}
\[(b) \quad X \text{ is weakly sequentially compact.}
\[(c) \quad X \text{ is weakly countably compact.}

**Proof.** Each one of the properties \((a), (b), (c)\) implies compactness of \( f(X) \) for all \( f \in E' \). By Theorem 2.1 \( X \) is weakly metrizable and from that the equivalence of \((a), (b), (c)\) follows easily.

**Note.** In Corollary 2.2, \((a), (b), (c)\) are obviously equivalent to: ‘for all \( f \in E' \) the image \( f(X) \) is compact.’

We have seen in the Introduction that Theorem 2.1 fails if \( K \) is locally compact. We now investigate what happens to Corollary 2.2. Note that every normed space over \( K \) has \((\ast)\).

**Theorem 2.3.** \((p\text{-adic Eberlein-Smulian Theorem II})\) Let \( K \) be locally compact, let \( X \subset E \). Then each one of the above statements \((a), (b), (c)\) is equivalent to ‘\( X \) is norm compact’.

**Proof.** We have \((a) \Rightarrow (c), (b) \Rightarrow (c)\). It suffices to prove that \((c)\) implies that \( X \) is a norm compactoid (then \( X \) is weakly metrizable since the norm and weak topology coincide on \( X \) \((6), 5.12)\)). Suppose not. Then by \([7], \text{Th. 2}\) there is a \( t \in (0, 1) \) and a \( t\)-orthogonal sequence \( e_1, e_2, \ldots \) in \( X \) such that \( \inf_n \|e_n\| > 0 \). By \((c)\) there is a weak accumulation point \( a \) of \( \{e_1, e_2, \ldots\} \). This \( a \) is in the weak closure \( D \) of \( \{e_1, e_2, \ldots\} \) which equals the norm closure, so \( a = \sum_{i=1}^{\infty} \lambda_i e_i \) where \( \|\lambda_i e_i\| \to 0 \). If \( \lambda_j \neq 0 \) for some \( j \), let \( U := \{x \in E : |\delta_j(x)| < |\lambda_j|\} \) where \( \delta_j \in E' \) is an extension of the \( j \)-th coordinate function \( \Sigma_j x_i e_i \mapsto \xi_j \) on \( D \). Then \( a + U \) is a weak neighbourhood of \( a \) but for each \( n \in \mathbb{N}, n \neq j \) we have \( |\delta_j (a - e_n)| = |\lambda_j| \) so \( e_n \not\in a + U \), a contradiction. Hence, \( a = 0 \).

But then \( \{x \in E : |f(x)| < 1\} \) is a weak neighbourhood of \( a \) containing no \( e_n \) if \( f \in E' \) is such that \( f(e_n) = 1 \) for all \( n \). Contradiction, so \( X \) is a norm compactoid.

**Remark.** Corollary 2.2 for strongly polar spaces \( E \) and Theorem 2.3 were first proved directly by the first author.
REMARK. The following 'relative' version of the Eberlein-Šmulian Theorem holds. (Compare [1], VIII §2, Theorem 1). Let $X \subset E$. Suppose one of the conditions (i), (ii), (iii) of Theorem 2.1 is satisfied. Then the following are equivalent. (a) $X$ is weakly relatively compact. (b) $X$ is weakly relatively sequentially compact. (c) $X$ is weakly relatively countably compact.

We leave the easy proof to the reader.

COUNTEREXAMPLES. We show that the previous theory fails for certain subsets $X$ of $\ell^\infty(I)$ where $I$ has at least the cardinality of the continuum, but is non-measurable, and where $K$ is not spherically complete.

Let $X := \{\xi_S : S \subset I\}$. Then $X$ is a weakly compact but not weakly sequentially compact subset of $\ell^\infty(I)$.

Proof. $X$ is bounded and since $\ell^\infty(I)' \simeq c_0(I)$ ([4], 4.21) the weak topology on $X$ is the topology of pointwise convergence. Clearly the map $f \mapsto (f(i))_{i \in I}$ is a homeomorphism $X \to \{0, 1\}^I$, hence $X$ is weakly compact. To prove that $X$ is not weakly sequentially compact, let $\phi : I \to Y$ be a surjection where $Y := \{\xi_S : A \subset N\} \subset \ell^\infty$. The formula $\phi(x) = (\xi_{S_1}(x), \xi_{S_2}(x), \ldots) (x \in I)$ defines subsets $S_1, S_2, \ldots$ of $I$. If $\xi_{S_1}, \xi_{S_2}, \ldots$ is a subsequence of $\xi_{S_1}, \xi_{S_2}, \ldots$ then, by surjectivity of $\phi$, there is an $x \in I$ for which $(\xi_{S_1}(x), \xi_{S_2}(x), \ldots) = (1, 0, 1, 0, 1, \ldots)$, so the subsequence is not weakly convergent.

2. Let $Z := \{\xi_S : S \subset I, S \text{ countable}\} \subset \ell^\infty(I)$. Then $Z$ is weakly sequentially compact but not weakly compact.

Proof. Clearly the weak closure of $Z$ equals $X$ of above, so $Z$ is not weakly compact. On the other hand, if $\xi_{S_1}, \xi_{S_2}, \ldots$ is a sequence in $Z$ then $S := \cup S_n$ is countable and by a standard diagonal procedure one obtains a subsequence converging at all points of $S$, hence at all points of $I$, to an element of $Z$.

3. Let $T := \{\xi_{i_n} : i \in I\} \subset \ell^\infty(I)$. Then $f(T)$ is compact for all $f \in \ell^\infty(I)'$ but $T$ is not weakly countably compact.

Proof. Let $f \in \ell^\infty(I)'$. As $\ell^\infty(I)' \simeq c_0(I)$ we have that $f(\xi_{i_1}) = 0$ except for $i \in \{i_1, i_2, \ldots\}$ where we may assume the $i_n \in I$ to be distinct. Then $\xi_{i_n} \rightharpoonup 0$ weakly so $T_1 := \{0\} \cup \{\xi_{i_n} : n \in N\}$ is weakly compact and $f(T_1) = f(T)$ is compact. However the only weak accumulation point of $\{\xi_{i_1}, \xi_{i_2}, \ldots\}$ is $0 \notin T$ so that $T$ is not weakly countably compact.

REFERENCES