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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 \( | \cdot | \), and \( E \) is a normed \( K \)-vector space, where we assume \( \| \cdot \| \) to satisfy the strong triangle inequality \( \| x + y \| \leq \max(\| x \|, \| y \|) \). We write \( |K^*| := \{ |\lambda| : \lambda \in K, \lambda \neq 0 \} \), \( B_E(0,r) := \{ x \in E : \| x \| \leq r \} \), \( B \):= \( B(0,1) \).

\( E' \) is the space of all linear continuous functions \( E \rightarrow K \). Equipped with the norm \( f \mapsto \sup\{ |f(x)| : x \in B \} \) it is a Banach space (i.e. a complete normed space). \( E \) is called normpolar if the norm is polar i.e. if \( \| x \| = \sup\{ |f(x)| : f \in E', |f| \leq \| \| \} \) \( \{ x \in E \} \), in other words, if \( g : E \rightarrow E'' \) 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.

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on $E'$ making all evaluation maps $f \mapsto f(a)$ ($a \in E$) continuous. For $X \subseteq E'$ we denote its $w'$-closure by $\overline{X}$. 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 $\{x \in E : \inf_{f \in E} |f(x)| > 0\}$ 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 $\bigcup_n U_n = \{x \in E : \inf_{f \in E} |f(x)| > 0\}$.

**Lemma 1.2.** Let $K$ be not locally compact. Let $X \subseteq E'$ and $a \in E$ be such that $X(a) := \{f(a) : f \in X\}$ is precompact. Suppose $X \subseteq g + U$ 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 $b \in E$ for which $\|a - b\| < \varepsilon$ and $\inf_{f \in E} |f(b)| : f \in X\} > 0$.

*Proof.* There exists an $r \in |K|$ such that $B_{E'}(0, r) \subseteq U$. 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 $C := \{\lambda \in K : |\delta| \leq |\lambda| \leq |\delta|\}$ 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

$$|f(a) - \gamma| \geq |\gamma| \quad (f \in X).$$

$U$ 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 $\|a - b\| = \|c\| = |b(c)| \leq |\gamma| r^{-1} \leq \varepsilon$. 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 $\inf_{f \in E} |f(b)| > 0$.

**Corollary 1.3.** Let $K$ be not locally compact, let $E$ be a Banach space. Let $X \subseteq E'$ be $w'$-precompact. Suppose $X \subseteq g + U$ where $U$ is an edged zero neighbourhood in $E'$, $U$ $w'$-closed, $g \in E' \setminus U$. Then $\{x \in E : \inf_{f \in E} |f(x)| > 0\}$ 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 $X \subseteq E'$ $\sigma$-decomposable in $E'$ if for each $g \in E' \setminus X$ there exist $f_1, f_2, \ldots \in X$ and edged zero neighbourhoods $U_1, U_2, \ldots$ in $E'$ such that each $U_n$ is $w'$-closed and $X \subseteq \bigcup_n (f_n + U_n), g \notin \bigcup_n (f_n + U_n)$.

**Theorem 1.5.** (Separation Theorem) Let $K$ be not locally compact, let $E$ be a Banach space, let $X \subseteq E'$ 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 $\{x \in E : \inf_{f \in E} |f(x)| > 0\}$ is open and dense in $E$, where $X_n := X \cap (f_n + U_n)$. By completeness and the Baire Category Theorem $\{x \in E : f(x) \neq 0 \text{ for all } f \in X\} \supset \bigcap_{n \in \mathbb{N}} \{x \in E : \inf_{f \in E} |f(x)| > 0\} \neq \emptyset$.

**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 $X \subseteq E$ 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 $f(a) \notin f(X)$. 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 $X \subseteq \bigcup_n (x_n + U_n), a \notin \bigcup_n (x_n + U_n)$.
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 $X(\alpha) := \{f(\alpha) : f \in X\}$ is compact for all $\alpha \in E$. Then $X$ is $w'$-compact.

Proof. The map $f \mapsto (f(\alpha))_{\alpha \in E}$ is a homeomorphism of $(E', w')$ onto a subspace of $K^E$.

The image of $X$ lies in the compact subset $\prod_{\alpha \in E} X(\alpha)$ so $X$ is $w'$-precompact. Since $E'$ is $w'$-quasicomplete 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 $\alpha \in E$ such that $g(\alpha) \notin X(\alpha)$. Now $X(\alpha) \subset \overline{X(\alpha)} = X(\alpha)$, so $g(\alpha) \notin \overline{X(\alpha)}$ i.e. $g \notin \overline{X(\alpha)}$.

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 $\max_{1 \leq i \leq n} |f(a_i)| \geq t||f|| \quad (f \in D)$.

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 a $(t, 1)$ 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 $g_i(b_j) = 1$ if $j \in \{1, \ldots, n\}$, $i \notin \{1, \ldots, n\}$. Let $i \in \{1, \ldots, n\}$, let $g = \sum_{j=1}^n \lambda_j g_j \in (E/H)'$. Then $||g|| \geq \sqrt{s} \max_{j=1}^n ||\lambda_j|| ||g_j||$ and $||g(b_i)|| = ||\lambda_i||$ so $||g(b_i)|| \leq \max_{j=1}^n ||\lambda_j|| ||g_j|| \leq \sqrt{s} ||g||$. So $||g|| < 1$. Thus, with $\pi : E \to E/H$ denoting the canonical quotient map, there exist $a_1, \ldots, a_n \in B_E$ with $||a_i|| = ||b_i||$ and $\pi(a_i) = b_i$ for each $i$. The adjoin $\pi' : \pi$ 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 $g = \sum_{j=1}^n \lambda_j g_j$, $\max_{1 \leq i \leq n} |f(a_i)| = \max_{1 \leq i \leq n} ||g(b_i)|| = \max_{1 \leq i \leq n} ||\lambda_i|| ||g_i|| \geq t||\lambda_i|| ||g_i|| = t||g|| = t||f||$.

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 $a_1, \ldots, a_n \in E$ with $||a_i|| = ||b_i||$ 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 $\max_{1 \leq i \leq n} |f(a_i)| \geq t||f||$ 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 $\max_{1 \leq i \leq n} |f(a_i)| \geq t||f||$ for all $f \in D_n$.

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

\[ (*) \quad \|f\| \geq \sup_{a \in F^1} |f(a)| \geq t\|f\| \quad (f \in D_n). \]

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

PROPOSITION 1.9. Let $X \subset E'$ be such that $X(\alpha) := \{f(\alpha) : f \in X\}$ is separable for each $\alpha \in E$ 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

\[ (*) \quad \|h\| = \sup_{n \in \mathbb{N}} |h(a_n)| \quad (h \in D). \]

For each $m, n \in \mathbb{N}$ the set $U_{mn} := \{h \in E' : |h(a_n)| \leq \frac{1}{m}\}$ 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 $f \in g + U_{mn}$ for all
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weak precompactness of is $\sigma$-decomposable in $j(X)$

$X =$ every (u/-) bounded subset of $X$ is weakly metrizable. Observe that $a$-decomposable in any the weak topology onto $j(E)$ so have strongly polar spaces ([7], 6.1) which applies to $E'$ is assumed to be normpolar. For case (ii) observe that $E'$ is of countable type, every $f \in E'$ 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 ($\sigma$). For general $K$, spaces with a base, in particular spaces of countable type, have ($\sigma$) ([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 ($\sigma$).
(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 $j(X) \cup \{\theta\}$ for any $\theta \in E''$. 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 $f_1, f_2, \ldots \in E'$ such that $\|j(x)\| = \sup_{n \in \mathbb{N}} |f_n(x)|$ for all $x \in X$. The formula $d(x, y) = \sup_{n \in \mathbb{N}} |f_n(x) - f_n(y)|2^{-n}$ defines an ultrametric $d$ 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 (6) $\Rightarrow$ (7)) but since $(\ell^\infty)' \simeq c_0$ ([4], 4.17) it satisfies (ii) of the above Theorem, and so do the non-reflexive space $\ell^\infty \overline{\oplus} \ell^\infty$ ([3], 2.3) and the space $D$ of [4], 4.J.

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 $\lim_{n \to \infty} e_n = 0$ 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 $E := \mathbb{F}_p$ with the product topology. Then $E' \cong \bigoplus K$. 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 $0 = w - \lim_{n \to \infty} e_n \notin X$.

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

**COROLLARY 2.2.** (p-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) $X$ is weakly compact.

(b) $X$ is weakly sequentially compact.

(c) $X$ 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-adic Eberlein-Šmulian 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], 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 $U := \{z \in E : |\delta_j(z)| < |\lambda_j|\}$ where $\delta_j \in E'$ is an extension of the $j$th coordinate function $\Sigma \xi_j e_i \mapsto \xi_j$ 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 $e_n \notin a + U$, a contradiction. Hence, $a = 0$. But then $\{z \in E : |\delta_j(z)| < 1\}$ 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: (α) $X$ is weakly relatively compact. (β) $X$ is weakly relatively sequentially compact. (γ) $X$ 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. The $K$-valued characteristic function of a subset $S \subset I$ is denoted $\xi_S$ and is given by $\xi_S(x) := 1$ if $x \in S$, $\xi_S(x) := 0$ if $x \in I \setminus S$.

1. 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 $\ell^\infty(I)' = c_0(I)$ ([4],4.21) the weak topology on $X$ is the topology of pointwise convergence. Clearly the map $f \mapsto (f(x))_{x \in I}$ 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 $Y := (\xi_A : A \subset \mathbb{N}) \subset \ell^\infty$. 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 $\xi_{S_2}, \xi_{S_2}, \ldots$ then, by surjectivity of $\phi$, there is an $x \in I$ for which $(\xi_{S_1}(x), \xi_{S_2}(x), \ldots) = (1,0,1,0,\ldots)$, 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 $S := \bigcup S_n$ 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 $T := \{t_i : i \in I\} \subset \ell^\infty(I)$. 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 $\ell^\infty(I)' = c_0(I)$ we have that $f(\xi_{i_n}) = 0$ except for $i \in \{i_1, i_2, \ldots\}$ where we may assume the $i_n \in I$ to be distinct. Then $\xi_{i_n} \to 0$ weakly so $T_1 := \{0\} \cup \{\xi_{i_n} : n \in \mathbb{N}\}$ is weakly compact and $f(T) = f(T_1)$ is compact. However the only weak accumulation point of $\{\xi_{i_1}, \xi_{i_2}, \ldots\}$ is $0 \not\in T$ so that $T$ is not weakly countably compact.

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