GILLES GODEFROY
D. LI

Banach spaces which are $M$-ideals in their bidual have property $(u)$


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BANACH SPACES WHICH ARE M-IDEALS IN THEIR BIDUAL HAVE PROPERTY (u)

by G. GODEFROY and D. LI

1. Introduction.

A Banach $X$ is an $M$-ideal in its bidual if the relation

$$\|y + t\| = \|y\| + \|t\|$$

holds for every $y \in X^*$ and every $t \in X^* \subseteq X^{***}$. The spaces $c_0(I) - I$ any set-equipped with their canonical norm belong to this class, which also contains e.g. certain spaces $K(E,F)$ of compact operators between reflexive spaces (see [11]) and certain spaces of the form $C(G)/C_\Lambda(G)$ where $G$ is an abelian compact group and $\Lambda$ is a subset of the discrete dual group (see [5]). This class has been carefully investigated, in particular by A. Lima and by the «West-Berlin school>>, since the notion of $M$-ideal was introduced by Alfsen and Effros in 1972 [1].

We will show in this paper that these spaces somehow «look like» $c_0$; more precisely, that they share the property (u) with this latter space. This solves affirmatively a question that was pending for several years, and provides improvements of some results of [6] and [10].

Our proof uses non-linear arguments. The key lemma is actually a special case of a fundamental lemma ([1], lemma 1.4.) of the original article of Alfsen and Effros.

Notation. — The closed unit ball of a Banach space $Z$ is denoted by $Z_1$, and its dual by $Z^*$. The topology defined on $Z^*$ by the pointwise convergence on $Z$ is denoted by $\omega^*$. The canonical injection from a Banach space $X$ into its bidual $X^{**}$ is denoted by $i$. A sequence $(x_n)$ in $X$ is said to be a weakly unconditionally convergent series —

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in short, w.u.c. series — if for every \( y \in X^* \),
\[
\sum_{m=0}^{\infty} |y(x_m)| < \infty.
\]

If \( (x_m) \) is a w.u.c. series, then clearly the sequence
\[
s_k = \sum_{m=0}^{k} x_m \quad (k \geq 1)
\]
is weakly Cauchy and thus it converges in \((X^{**}, w^*)\); we note \( \Sigma^* x_m = \lim_{k \to \infty} (s_k) \) in \((X^{**}, \omega^*)\). A Banach space \( X \) has the property (u) ([14]; see [12], p. 32) if every \( z \in X^{**} \) which is in the sequential closure of \( X \) in \((X^{**}, \omega^*)\) may be written
\[
z = \Sigma^* x_m
\]
for some w.u.c. series \( (x_m) \) in \( X \).

If \( \tau : Z_1^* \to \mathbb{R} \) is a real-valued function defined on a dual unit ball \( Z_1^* \), we denote by \( \hat{\tau} \) the smallest concave \( \omega^* \)-u.s.c. function which is greater than \( \tau \) on \( Z_1^* \). The function \( \hat{\tau} \) is the infimum of the affine continuous functions on \((Z_1^*, \omega^*)\) which maximize \( \tau \) on \( Z_1^* \). The reader should consult [2] for a presentation of the basic facts about \( M \)-ideals. Similar ideas to those we use in this work are to be found e.g. in [15].

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2. The main result.

We will now prove:

Theorem 1. — Let \( X \) be a Banach space which is an \( M \)-ideal in its bidual. Then \( X \) has the property \( (u) \).

Proof. — If \( i \) denotes the canonical injection from \( X \) into \( X^{**} \), \( i^{**} \) is an isometric injection from \( X^{**} \) into \( X^{****} \) which is distinct from
the canonical injection if $X$ is not reflexive. We will use a simplified notation that we now define: $i^*$ denotes the canonical projection from $X^{***}$ onto $X^*$ of kernel $i(X)^1 = X^1$, and then of course $i^{**}(z) = z \circ i^*$.

From now on, we assume that $X$ is a real Banach space. By ([2], p. 22), we can do so without loss of generality. The notation $1_{X^1}$ denotes the characteristic function of the subset $X^1$ of the unit ball $X^{***}$ of $X^{***}$. Thus for any $z \in X^{***}$, $(1_{X^1}, z \vee 0)$ denotes the supremum of 0 and of the pointwise product of $z$ and $1_{X^1}$.

With this notation, we have the following crucial lemma.

**Lemma 2.** — *If $X$ is an $M$-ideal in its bidual $X^{**}$, then for every $z \in X^{**}$ and every $t \in X^{***}$ one has*

$$<z - i^{**}(z), t> = [1_{X^1} - z \vee 0](t) - [1_{X^1} - z \vee 0](t).$$

This lemma is actually a special case of ([1], lemma 1.4). For sake of completeness, we give a simplified proof of this special case.

**Proof.** — If $\Psi$ is a function from $X^{***}$ to $R^+$, we define

$$\mathcal{G}^- (\Psi) = \{(t, \lambda) \in X^* \times R^+ | 0 \leq \lambda \leq \Psi(t)\}$$

we let $\tau = (1_{X^1}, z \vee 0)$, and

$$B = \{(t, z(t)) \in X^1 \times R^+ | z(t) \geq 0\}.$$

We clearly have

$$(1) \quad \mathcal{G}^- (\tau) = \operatorname{conv} (\mathcal{G}^-(\tau)).$$

On the other hand,

$$(2) \quad X^{***} = \operatorname{conv} (X^* \cup X^1) \text{ since } X \text{ is an } M\text{-ideal in } X^{**}$$

$$(3) \quad \text{if } 0 \leq \lambda \leq z(t), \ (t, \lambda) \in \operatorname{conv} \{(t, 0); (t, z(t))\}.$$

From (1), (2) and (3) follows

$$\mathcal{G}^- (\tau) = \operatorname{conv} (\mathcal{G}^-(\tau))$$

$$= \operatorname{conv} \{(X^{***} \times \{0\}) \cup B\}$$

$$= \operatorname{conv} \{(X^* \times \{0\}) \cup (X^1 \times \{0\}) \cup B\}$$

since by $w^*$-compactness we don’t need to take $w^*$-closures.
For every $t \in X^\ast\ast$, $(t, \tilde{t}(t)) \in \mathcal{G}^{-}(\tilde{t})$, hence we may write
$(t, \tilde{t}(t)) = \alpha_1(t_1, 0) + \alpha_2(t_2, 0) + \alpha_3(t_3, z(t_3))$ with:

$$
\begin{align*}
&\begin{cases}
  t_1 \in X^* \\
  t_2 \in X_1^\perp \\
  t_3 \in X_1^\perp; \quad z(t_3) \geq 0
\end{cases}
\end{align*}
$$

$\alpha_1, \alpha_2, \alpha_3 \geq 0$, $\alpha_1 + \alpha_2 + \alpha_3 = 1$.

Since $t = \alpha_1 t_1 + (\alpha_2 t_2 + \alpha_3 t_3)$ is the unique decomposition of $t$ on the direct sum $X^* \oplus X_1^\perp$, one has

$$t - i^*(t) = \alpha_2 t_2 + \alpha_3 t_3.$$ 

Since $z(t_3) \geq 0$, one has $\tau(t_3) = z(t_3)$ and $\tau(-t_3) = 0$. Since $\tilde{t}$ is concave, one has

$$\tilde{t}(t) = \alpha_3 z(t_3)$$

$$\geq \sum_{i=1}^{3} \alpha_i \tilde{t}(t_i)$$

$$\geq \sum_{i=1}^{3} \alpha_i \tau(t_i)$$

$$= \alpha_2 \tau(t_2) + \alpha_3 \tau(t_3)$$

$$= \alpha_2 \tau(t_2) + \alpha_3 z(t_3)$$

hence $\alpha_2 \tau(t_2) \leq 0$; if $\alpha_2 = 0$ we may take $t_2 = 0$ as well; if $\alpha_2 > 0$ this implies $\tau(t_2) \leq 0$, hence $z(t_2) \leq 0$. In both cases, we have $z(-t_2) \geq 0$ and thus $z(-t_3) = \tau(-t_2)$.

Again by concavity of $\tilde{t}$, one has

$$\tilde{t}(-t) \geq \sum_{i=1}^{3} \alpha_i \tilde{t}(-t_i)$$

$$\geq \sum_{i=1}^{3} \alpha_i \tau(-t_i)$$

$$= \alpha_2 \tau(-t_2) + \alpha_3 \tau(-t_3)$$

$$= \alpha_2 z(-t_2)$$

hence

$$- \tilde{t}(-t) \leq \alpha_2 z(t_2)$$

and therefore

$$\tilde{t}(t) - \tilde{t}(-t) \leq \alpha_2 z(t_2) + \alpha_2 z(t_2)$$
and
\[
\alpha_3 z(t_3) + \alpha_3 z(t_2) = \langle z, \alpha_3 t_2 + \alpha_3 t_3 \rangle \\
= \langle z, t - i(t) \rangle \\
= \langle z - i**(z), t \rangle.
\]

Now the functions \( \Phi(t) = \tilde{\tau}(t) - \tilde{\tau}(-t) \) and \( z - i**(z) \) are both odd functions on \( X_{-1}^{**} \) and they satisfy \( \Phi \leq z - i**(z) \); hence necessarily \( \Phi = z - i**(z) \) on \( X_{-1}^{**} \).

We now come back to the proof of theorem 1. By lemma 2, for every \( z \in X_{**} \), we can write
\[
\forall t \in X_{-1}^{**}, \quad \langle i**(z), t \rangle = (z(t) - \tilde{\tau}(t)) + \tilde{\tau}(-t)
\]
hence if we let
\[
h_1(t) = z(t) - \tilde{\tau}(t) \\
\tilde{h}_2(t) = - \tilde{\tau}(-t)
\]
we have \( i**(z) = h_1 - \tilde{h}_2 \) and \( h_1, \tilde{h}_2 \) are both l.s.c. on \( (X_{-1}^{**}, w^*) \).

We need now a topological argument for going down to \( (X_{-1}^{**}, w^*) \).

**Lemma 3 (Saint-Raymond).** Let \( K \) be a compact topological space and \( S : K \to K' \) be a continuous surjection. Let \( f \) be a function from \( K \) to \( \mathbb{R} \) which is such that \( f \circ S \) is the difference of two l.s.c. functions on \( K \). Then \( f \) is the difference of two l.s.c. functions on \( K' \).

**Proof.** Write \( f \circ S = g_1 - g_2 \) where \( g_1, g_2 \) are l.s.c. on \( K \); we define for \( y \in K' \)
\[
\tilde{g}_1(y) = \inf \{ g_1(t) \mid S(t) = y \} \\
\tilde{g}_2(y) = \inf \{ g_2(t) \mid S(t) = y \}
\]
the functions \( \tilde{g}_i(i=1,2) \) are l.s.c. on \( K' \). Indeed, pick \( \alpha < \tilde{g}_i(y) \); this means
\[
(1) \quad \forall t \in S^{-1}(y), \quad g_i(t) > \alpha.
\]
Since \( g_i \) is l.s.c. and \( S^{-1}(y) \) is compact, (1) implies that there exists \( \varepsilon > 0 \) and an open neighbourhood \( V \) of \( S^{-1}(y) \) such that
\[
(2) \quad \forall t \in V, \quad g_i(t) > \alpha + \varepsilon.
\]
Again by compactness, there exists a neighbourhood \( W \) of \( y \) such
that $S^{-1}(W) \subseteq V$; by (2) and the definition of $g_i$, this implies

$$\forall y' \in W, \quad \tilde{g}_i(y') \geq \alpha + \varepsilon > \alpha$$

and thus $\tilde{g}_i$ is l.s.c.

We show now that $f = \tilde{g}_1 - \tilde{g}_2$; for every $y \in K'$ and $t \in S^{-1}(y)$, one has

$$\tilde{g}_1(y) \leq g_1(t) = f \circ S(t) + g_2(t)$$

hence by definition of $\tilde{g}_2$

$$\tilde{g}_1(y) \leq f(y) + \tilde{g}_2(y).$$

On the other hand,

$$f(y) + \tilde{g}_2(y) \leq f(y) + g_2(t)$$

$$= f \circ S(t) + g_2(t)$$

$$= g_1(t)$$

and thus by definition of $\tilde{g}_1$,

$$f(y) + \tilde{g}_2(y) \leq \tilde{g}_1(y)$$

and this concludes the proof of lemma 3. \hfill \Box

Let us now conclude the proof of the theorem. Since

$$i^{**}(z) = z \circ i^* = h_1 - h_2$$

with $h_1$ and $h_2$ l.s.c. on $(X^{***}, w^*)$, we may apply lemma 3 with $f = z$, $S = i^*$ and $K' = (X^*_i, w^*)$; this lemma provides us with the l.s.c. functions $\tilde{h}_1$ and $\tilde{h}_2$ on $(X^*_i, w^*)$ such that $z = \tilde{h}_1 - \tilde{h}_2$.

If now $z = \lim_{n \to \infty} x_n$ in $(X^{**}, w^*)$, where $(x_n)$ is a sequence in $X$, we let

$$Y = \text{span} \{ x_n | n \geq 1 \}$$

and we call $Q$ the canonical quotient map from $X^*$ onto $Y^*$; since $z \in Y^{**} = Q^*(Y^{**})$, there is $z' \in Y^{**}$ such that $z = z' \circ Q$; again by lemma 3, there exist two l.s.c. functions $\tilde{h}_1$ and $\tilde{h}_2$ on $(Y^*_i, w^*)$ such that

$$z' = \tilde{h}_1 - \tilde{h}_2.$$
But since $Y$ is separable, the $w^*$-topology on $Y_1^*$ is defined by a metric $d$, and then classically the sequences $f_n^i (i=1,2)$ defined for $y \in Y_1^*$ and $n \geq 1$ by

$$f_n^i (y) = \inf \{ \tilde{h}_i (y') + nd(y,y') \mid y' \in Y_1^* \}$$

are increasing sequences of continuous functions on $(Y_1^*, w^*)$ which converge pointwise to $\tilde{h}_i$. Now the sequence $u_n (n \geq 0)$ of continuous functions on $(Y_1^*, w^*)$ defined by

$$u_0 = f_1^1 - f_1^2$$
$$u_n = f_{n+1}^1 + f_n^2 - f_n^1 - f_{n+1}^2 \quad (n \geq 1)$$

satisfies

$$\sum_{n=0}^{\infty} |u_n(y)| < \infty, \quad \forall y \in Y_1^*$$

and

$$\sum_{n=0}^{\infty} u_n(y) = z'(y), \quad \forall y \in Y_1^*.$$  

But we still have

$$z'(y) = \lim_{n \to \infty} x_n(y), \quad \forall y \in Y_1^*$$

in this situation, a classical lemma of Pelczynski [14] (see [12], p. 32), which relies on a convex combination argument, shows that there is a sequence $(c_n)_{n \geq 0}$ in $Y$ with

$$\sum_{n=0}^{\infty} |c_n(y)| < \infty, \quad \forall y \in Y_1^*$$

and

$$\sum_{n=0}^{\infty} c_n(y) = z'(y), \quad \forall y \in Y_1^*$$

and since $z = Q^*(z')$ and $c_n = Q^*(c_n)$, this shows that

$$z = \sum c_n$$

and $(c_n)$ is a w.u.c. series in $X$. \hfill \square

Before mentioning a few applications of our result, we would like to mention that the proof provides an explicit expression of $z \in X^{**}$.
as a difference of two l.s.c. functions on \((X^*_1, w^*_1)\); indeed, if we define for \(y \in X^*_1\)

\[
v(y) = \inf \{ z(t) - [1_{x^*_1} \circ z \vee 0](t) | t \in X^{***}_1, \ t^*(t) = y \}
\]

then the functions \(v\) and \((v-z)\) are both l.s.c. on \((X^*_1, w^*_1)\).

3. Applications.

We gather in this section a few consequences of our result.

3.1. P. Saab and the first-named author showed in ([6], Theorem 1) that if \(X\) is an \(M\)-ideal in its bidual then \(X\) has the property \((V)\) of Pelczynski; the proof uses « pseudo-balls » ([3]) and the local reflexivity principle. Since such an \(X\) does not contain \(\ell^1(N)\), our result is an improvement of ([6], Theorem 1), and of course also of the fact ([10]) that non-reflexive \(M\)-ideals in their bidual contain \(c_0(N)\).

Another result of [6] is a structural result (Corollary 6) for certain spaces \(E\) such that \(K(E)\) is an \(M\)-ideal in \(L(E)\). The proof uses Banach algebras techniques that require to work with complex Banach spaces. This is not needed any more, and our result together with the proofs of ([6], Theorem 4 and Corollary 6) implies for instance the

**Proposition 4.** — Let \(E\) be a separable reflexive space with A.P. such that \(K(E)\) is an \(M\)-ideal in \(L(E)\). Then \(E\) is complemented in a reflexive space with an unconditional finite dimensional decomposition.

There are some similarities between the techniques of [6] and of the present work; the main difference is that instead of using l.s.c. affine functions on a non-symmetric convex set — namely, the state space of a Banach algebra — we employ l.s.c. convex functions on a symmetric convex set — namely, a dual unit ball.

3.2. A Banach space \(Y\) is said to have to property \((X)\) [7] if the following holds: \(z \in Y^{**}\) belongs to \(Y\) if and only if for every w.u.c. series \((y_n)\) in \(Y^*\),

\[
z(\Sigma y_n) = \Sigma z(y_n)
\]

where \((\Sigma y_n)\) denotes the limit of the sequence \(s_k = \sum_{n=1}^{k} y_n | k \geq 1\) in \((Y^*, w^*)\). This condition roughly means that an abstract Radon-
Nikodym theorem is available for deciding which elements of $Y^{**}$ belong to $Y$. Property (X) is equivalent to saying that $Y < \ell^1(N)$ for Edgar's ordering of Banach spaces [4]. For more details about this property, the reader may consult the recent survey [8].

Let us recall now the following easy

Claim. — If $X$ is separable, does not contain $\ell^1(N)$ and has the property (u), then $X^*$ has the property (X).

Proof of the claim. — We must show that every $t \in X^{***}$ such that $t(\Sigma_n z_n) = \Sigma t(z_n)$ for every w.u.c. series in $X^{**}$ belongs to $X^*$. We can write $t = y + t'$ with $y \in X^*$ and $t' \in X^\perp$; since $y(\Sigma_n z_n) = \Sigma y(z_n)$ by $w^*$-continuity of $y$, we also have $t'(\Sigma_n z_n) = \Sigma t'(z_n)$.

Since $X$ is separable, does not contain $\ell^1(N)$ and has (u), every $z \in X^{**}$ can be written $z = \Sigma^* x_n = \Sigma^* i(x_n)$ for some w.u.c. series in $X$; but since $t'(x_n) = 0$ for every $n$, this implies $t'(z) = 0$, hence $t' = 0$ and $t = y \in X^*$.

Now this claim, together with theorem 1, shows:

Proposition 5. — If a separable Banach space $X$ is an M-ideal in its bidual, then $X^*$ has the property (X).

By ([8], Theorem VII.8) this implies the following

Corollary 6. — Let $X$ be a separable Banach space $X$ which is an M-ideal in its bidual, and let $Y$ be an arbitrary Banach space. Let $T : X^{**} \to Y^*$ be a bounded linear operator. The following are equivalent:

1. there is an operator $T_0 = Y \to X^*$ such that $T_0^* = T$,
2. $\ker (T)$ and $T(X^{**})$ are $w^*$-closed,
3. $T$ is $(w^* - w^*)$-Borel,
4. $T$ is $(w^* - w^*)$-strongly Baire measurable.

Let us conclude this work with a few natural questions.

Question 3.4. — Does there exist a separable Asplund space with property (u) which is not isomorphic to an M-ideal in its bidual? It looks reasonable to believe that this question has a positive answer; a candidate example is the space $K(L^p)(1 < p < \infty, p \neq 2)$ which has (u) ([12], Th. 3) but is not M-ideal of its bidual for its canonical norm [11].
Let us also mention that a separable $\mathcal{L}^\infty$-space which is isomorphic to an $M$-ideal in its bidual is in fact isomorphic to $c_0(N)$ [9]. We do not know whether any isomorphic predual of $\ell^1(N)$ which has property (u) is isomorphic to $c_0(N)$.

**Question** 3.5. — A reformulation of Proposition 5 is that if $Y$ is a separable space such that there exists a projection $\pi : Y^{**} \rightarrow Y$ with:

(a) $\|z\| = \|\pi(z)\| + \|z - \pi(z)\|$, $\forall z \in Y^{**}$

(b) $(\ker \pi)$ $w^*$-closed,

then $Y$ has the property (X). It is not known whether the assumption (b) can be removed, or whether (a) alone implies the weaker property ($V^*$) (see [14]), or at least that $Y$ contains a complemented copy of $\ell^1(N)$ if it is not reflexive.

**BIBLIOGRAPHY**


G. Godefroy,
Université de Paris VI
Équipe d'Analyse
Tour 46-0, 4e étage
4, place Jussieu
75252 Paris Cedex 05.

D. Li,
Université de Paris-Sud
Mathématiques
Bâtiment 425
91405 Orsay Cedex.