TWO-NORM SPACES AND DECOMPOSITIONS OF BANACH SPACES. II

BY

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ABSTRACT. Let $X$ be a Banach space, $Y$ a closed subspace of $X^*$. One says $X$ is $Y$-reflexive if the canonical imbedding of $X$ onto $Y^*$ is an isometry and $Y$-pseudo reflexive if it is a linear isomorphism onto. If $X$ has a basis and $Y$ is the closed linear span of the corresponding biorthogonal functionals, necessary and sufficient conditions for $X$ to be $Y$-pseudo reflexive are due to I. Singer. To every $B$-space $X$ with a decomposition we associate a canonical two-norm space $X_s$ and show that the properties of $X_s$, in particular its $\gamma$-completion, may be exploited to give different proofs of Singer's results and, in particular, to extend them to $B$-spaces with decompositions. This technique is then applied to a study of direct sum of $B$-spaces with respect to a $BK$ space. Necessary and sufficient conditions for such a space to be reflexive are obtained.

1.0 Introduction. Given a Banach space (B-space for short) $(X, \| \cdot \|_1)$ with a Schauder decomposition $\{X_j\}$, a two-norm space $X_s$, called the canonical two-norm space of $X$, was introduced in [10] and the properties of $X$ were then studied by investigating the properties of $X_s$. The aim of this paper is to continue these investigations and, in particular, study the so-called pseudo reflexivity of $X$ with respect to $A(X_s)$, the $\gamma$-linear functionals on $X_s$. Some of our results generalize those of Singer [9] to the setting of Schauder decompositions providing, at the same time, a slightly different method of proof of these results.

The basic topic of our discussion is the notion of $\gamma$-completion of the canonical two-norm space. A canonical two-norm space may be defined whenever $X$ is the direct sum of subspaces for a metric topology, not necessarily the norm topology. In §§5–7, we study spaces $X = B + X_n$ of sequences $\{x_n\}$ where $x_n$ belongs to a $B$-space $X_n$ such that $\|x_n\|$ is an element of a given $BK$ space $B$ of real sequences. We extend the notions of boundedly complete and shrinking decompositions to this setting and obtain analogues of some of the results in Schauder decomposition theory (cf. [10]).
2.0 Notations and preliminaries. A (weak) decomposition \(|X_j|\) for a B-space \((X, | |)\) is a collection \(|X_j|\) of nontrivial subspaces of \(X\) such that to each \(x\) in \(X\), there corresponds a unique sequence \(|x_j|, x_j\) in \(X_j\), and \(x = \sum_j x_j\) in the norm (respectively weak) topology of \(X\). It is called a Schauder decomposition of \(X\), if for each \(j\) the projection map \(P_j: X \rightarrow X_j\) defined by \(P_j(x) = x_j\), is continuous. The decomposition \(|X_j|\) is called boundedly complete if every sequence \(|x_j|, x_j\) in \(X_j\), with the property

\[
\sup_n \left\{ \left| \sum_{k=1}^n x_k \right| \right\} < \infty
\]

defines an element of \(X\), that is, \(\sum_j x_j\) converges. The decomposition \(|X_j|\) is called shrinking for \(f\) in \(X^*\) if \(|f|_n^* \rightarrow 0\) as \(n \rightarrow \infty\), where

\[
|f|^*_n = \sup_n \left\{ |f(x)|: |x| \leq 1, x \in \sum_{j>n} X_j \right\}.
\]

In this paper all decompositions are assumed to be monotone, that is, \(\sum_j x_j \leq \sum_k x_k\) for all \(n\). The reader will later observe that the proofs of analogues of our theorems to the nonmonotone case present no difficulties.

A two-norm space \(X_s = (X, |||_1, |||_2)\) is a linear set \(X\) with two norms \(|||_1\) and \(|||_2\). In general, the second norm \(|||_2\) is an \(F\)-norm although, in most cases of interest, it is the usual (homogeneous) norm. In this paper, all two-norm spaces considered are such that \((X, |||_1)\) is a Banach space and \((X, |||_2)\) is a normed linear space. An exception occurs in §4 where the second norm is a \(B^*_0\)-norm. We recall that a \(B^*_0\)-norm \(|||_2\) on \(X\) is such that

\[
|||_2 = \sum_k 2^{-k} [x]_k/(1 + [x]_k),
\]

\([\cdot]_k\) being homogeneous pseudo norms such that \([x]_k = 0\) for all \(k\) implies \(x = 0\).

A sequence \(|x_n| \subset X_s\) is said to be \(\gamma\)-convergent to \(x\) in \(X_s\), written \(x_n \gamma \rightarrow x\), if \(|||x_n|_1\) is bounded and \(x_n \rightarrow x\) in \(|||_2\). A \(\gamma\)-Cauchy sequence is defined analogously and \(X_s\) is called \(\gamma\)-complete if it is sequentially complete for the convergence \((\gamma)\). The space \(X_s\) is called normal if

\[
x_n \gamma \rightarrow x \Rightarrow |||_1 \leq \lim inf |||_n\).
\]

A \(\gamma\)-linear functional on \(X_s\) is a linear functional which is continuous for the convergence \((\gamma)\). The set of all \(\gamma\)-linear functionals on \(X_s\) will be denoted by \(A(X_s)\).

We shall say that the space \(X_s\) satisfies property \((n_0)\) if \(|||_2\) is coarser than \(|||_1\), that is, every sequence that converges to 0 in \(|||_1\) does so in \(|||_2\) as well.

Let \((X_j^*, |||_j^*) = (X, |||_j)^*\), \(j = 1, 2\). For a normal two-norm space satisfying \((n_0)\), it is known that
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$X^*_2 \subseteq A(X^*_s) \subseteq X^*_1$,

$A(X^*_s)$ is a closed subspace of $X^*_1$ and that $A(X^*_s)$ is the closure of $X^*_2$ in $(X^*_1, \| \cdot \|_1^*)$. Further, $A(X^*_s)$ is norm determining, that is,

$$\| x \|_1 = \sup \{ \| f(x) \| : f \in A(Y^*_s) \}.$$ 

The space $X^*_s$ is called $\gamma$-reflexive if $(A(X^*_s), \| \cdot \|_1^*) = (A(X^*_s)^*, \| \cdot \|_1^*)$ is isometrically isomorphic to $(X, \| \cdot \|_1)$ under the canonical map $J$, where for $x$ in $X$, $J(x)f = f(x)$ for all $f$ in $A(X^*_s)$. Whenever $A(X^*_s) = X^*_1$, $X^*_s$ is called saturated.

Let $\{X_j\}$ be a decomposition for the $B$-space $(X, \| \cdot \|_1)$. The canonical two-norm space $X_s$ of $X$ is the two-norm space $(X, \| \cdot \|_1, \| \cdot \|_2)$, where for $x = \sum_j x_j$ in $X$,

$$\| x \|_2 = \sum_j \| x_j \|_1/2^j.$$ 

The norm $\| \cdot \|_2$ is called the canonical second norm. We shall continue to use the symbol $X^*_1$ for $(X, \| \cdot \|_1^*)$ and $X^*_2$ for $(X, \| \cdot \|_2^*)$. The reader should not confuse these symbols for the duals of the subspaces $X_1$ and $X_2$ respectively. This confusion can be easily avoided if he remembers that the duals of the subspaces themselves are nowhere considered in this paper.

The basic properties of the canonical two-norm space may be found in [10]. However, for the convenience of the reader, we recall the following notions and notations that are necessary for an understanding of the present paper.

Let $(X, \| \cdot \|_1)$ be a $B$-space with Schauder decomposition $\{X_j\}$, $P_j$ the continuous projection of $X$ onto $X_j$ and let $X_s$ be the canonical two-norm space. Then $A(X^*_s)$ has the Schauder decomposition $\{P_j^*(X^*_1)\}$. To simplify notation, we shall often write $A(X^*_s)$ for $P_j^*(X^*_1)$. The canonical two-norm space of $A(X^*_s)$ will be referred to as the $k$-dual of $X^*_s$ and will be denoted by $k\cdot X^*_s$. The Schauder decomposition of $A(k\cdot X^*_s)$ will be denoted by $\{A(k\cdot X^*_s)\}$ and the canonical two-norm space $A(k\cdot X^*_s)$ of $A(k\cdot X^*_s)$ by $k^2\cdot X^*_s$. When $\{X_j\}$ is monotone, the canonical map $J$ is an isometry (with respect to both norms) of $X^*_s$ into $k^2\cdot X^*_s$. When this map is also onto, one says $X^*_s$ is $k$-reflexive. Finally, we use the symbol $\Sigma^*$ to indicate convergence in the weak-* topology of a given dual space.

3.0 The $\gamma$-completion of $X^*_s$. Let $(X, \| \cdot \|_1)$ be a $B$-space with Schauder decomposition $\{X_j\}$ and canonical two-norm space $X^*_s$. As a consequence of [10, Theorem 3.6], it follows that $X^*_s$ may not, in general, be $\gamma$-complete. We shall now show that $X^*_s$ may be imbedded isometrically isomorphically into a $\gamma$-complete, normal two-norm space $C(X^*_s)$ such that $X^*_s$ is $\gamma$-dense in $C(X^*_s)$.

Theorem 3.1. The sets

$$\{ \| J(x_j) \| : x_j \in X_j, \sup_n \left[ \sum_{j \leq n} \| J(x_j) \|_1^* \right] < \infty \}$$ 


and
\[ \{ |f(x_j)| : \sum_{j \in I}^* f(x_j) \text{ converges in } \sigma(A(X_s), A(X_s)) \} \]

are identical.

**Proof.** Consider \( \{ f(x_j) \} \subset A(X_s)^* \) such that \( \| \sum_{j \in I}^* f(x_j) \|_1 \) is finite. Since \( A(X_s) \) is the norm-closure of the set \( \bigcup_k P_k(X_s) \) in \( X_s^* \) [2, p. 277], and \( \| \sum_{k \leq n} f(x_k) \| \) converges pointwise on \( \bigcup_k P_k(X_s) \), it follows by the Banach-Steinhaus theorem that \( \sum_{k \leq n} f(x_k) \) converges as desired.

Conversely the convergence of \( \sum_{k \leq n} f(x_k) \) implies, by the Uniform Boundedness Principle, that \( \sup_n \| \sum_{j \in I}^* f(x_j) \| \) is finite and the proof is complete.

Let \( C(X) = \{ |f(x_j)| : \sum_{j \in I}^* f(x_j) \text{ converges in } \sigma(A(X_s), A(X_s)) \} \). As a consequence of Theorem 3.1, we may equip \( C(X) \) with the norm \( \| \|_1^* \) defined by
\[ \| f(x_j) \|_1^* = \sup_n \left| \sum_{j \in I}^* f(x_j) \right| \]
and a canonical second norm \( \| \|_2^* \) defined by
\[ \| f(x_j) \|_2^* = \sum_j \frac{|f(x_j)|_1^*}{2^j} = \sum_j \frac{|x_j|_1}{2^j} . \]

**Theorem 3.2.** Let \( C(X_s) = (C(X), \| \|_1^*, \| \|_2^*). \) Then \( C(X_s) \) is \( \gamma \)-complete, normal and the map \( i \) defined for \( x = \sum_{j \in I}^* x_j \) in \( X \) by \( i(x) = \{ f(x_j) \} \) is a linear isomorphism of \( X \) into \( C(X) \). Further, \( i \) is an isometry with respect to both norms and \( i(X_s) \) is \( \gamma \)-dense in \( C(X_s) \).

**Proof.** Let \( \{ p_k \} \) denote the sequence of projections associated with the Schauder decomposition of \( A(X_s) \). By [10, Theorem 6.2] this decomposition is monotone so that the decomposition constant \( K_2 \) of \( A(X_s) \) is 1. Hence for any \( F = \sum_{k \leq n}^* p_k(F) \) in \( A(X_s)^* \),
\[ \| F \|_1^* \geq \sup_n \left| \sum_{k \leq n}^* p_k(F) \right| . \]
The reverse inequality being trivial, we obtain equality in (A). Let now \( \{ F_n \} \) be a \( \gamma \)-Cauchy sequence in \( C(X_s) \) where \( F_n = \{ f(x_{n,k}) \} \), \( x_{n,k} \in X_k. \) Then \( \sup_n \| F_n \|_1^* \) = \( K \) and \( \| f(x_{n,k}) - f(x_{m,k}) \|_1 \) \( \to 0 \) as \( n, m \to \infty, k = 1, 2, \ldots \). Since \( f(x_k) \) is complete, there exists \( y_k \in X_k \) such that \( f(x_{n,k}) \to f(y_k), k = 1, 2, \ldots \). Let \( f \in A(X_s) \) with \( \| f \|_1^* \) = 1. For any arbitrary but fixed \( m \),
\[ \sum_{k \leq m}^* f(y_k) = \lim_n \left| \sum_{k \leq m}^* f(x_{n,k}) \right| \leq \lim_n \left| \sum_{k \leq m}^* f(x_{n,k}) \right| \leq \inf_n \| F_n \|_1 \leq K \]
so that, by Theorem 3.1, \( \{f(y_k)\} \in C(X) \). Hence \( C(X) \) is \( \gamma \)-complete and this proof may also be used to show that it is normal.

The map \( i \) is obviously well defined. It is 1-1 since \( \{x_j\} \) is a Schauder decomposition of \( X \). That it is an isometry with respect to \( \| \cdot \|_1 \) and \( \| \cdot \|_2 \) is a consequence of the normality of \( X \), and the fact that \( \sum x_k = x \) in \( X \) whenever \( \sum_j j(x_k) = J(x) \) in \( A(X) \) and conversely.

Finally for \( \{f(x_k)\} \in C(X) \), \( \sum_{k \leq n} j(x_k) \in i(X) \) and \( \{\sum_{k \leq n} j(x_k)\} \rightarrow \{f(x_k)\} \). Hence \( i(X) \) is \( \gamma \)-dense in \( C(X) \) and the proof is complete.

We note that if \( \{x_j\} \) is nonmonotone, \( i \) reduces to a linear isomorphism with respect to both norms.

As an illustration of this last theorem, observe that the unit vectors \( \{e_n\}, e_n = \delta_{n,j}, \) form a nonboundedly complete basis for \( c_0 \), so that \( c_0 \) is not \( \gamma \)-complete. Its completion is \( m_s = (m, \sup_n |a_n|, \sum |a_n|/2^n) \). Here, however, \( m = l^* = A(c_{0,s})^* \). We shall soon see that this is a characteristic property of bases in \( B \)-spaces.

We also note that \( C(X) \) is isometrically isomorphic to the set of all sequences \( \{x_n\}, x_n \in X_n, \) such that \( \sup_n \left| \sum_{k \leq n} x_k \right|_1 < \infty \) with the norm (cf. [9])

\[
\|x_n\| = \sup_n \left| \sum_{k \leq n} x_k \right|_1
\]

**Definition 3.3.** Let \( X \) be a \( B \)-space with a (monotone) Schauder decomposition. The two-norm space \( C(X) \) of Theorem 3.2 is called the canonical \( \gamma \)-completion of \( X \). The space \( C(X) \) is called the bounded completion of \( X \).

**Theorem 3.4.** Let \( \{X_j\} \) be a (monotone) Schauder decomposition of a \( B \)-space \( X \). Then \( C(X) \) is identical with \( A(X_s)^* \) if and only if \( X_s \) is \( \gamma \)-reflexive.

**Proof.** Let \( I \) be the identity map on \( A(X_s)^* = \bigoplus_j A(k-X_s)_j \), where \( \{A(k-X_s)_j\} \) denotes the Schauder decomposition of \( A(k-X_s)_j \). By definition, \( C(X) = \bigoplus_j j(X_j) \), where \( j(X_j) \subseteq A(k-X_s)_j \) [9, Theorem 4.4]. Hence \( I: C(X) \rightarrow A(X_s)^* \). We thus have

\[
I \text{ is onto} \iff \bigoplus_j j(X_j) = \bigoplus_j A(k-X_s)_j
\]

\[
\iff j(X_j) = A(k-X_s)_j, \quad j = 1, 2, \ldots,
\]

\[
\iff j: X_s \twoheadrightarrow k^2-X_s
\]

\[
\iff X_s \text{ is } \gamma \text{-reflexive}
\]

by [9, Theorem 4.7] and this concludes the proof.

**Corollary 3.5.** For a \( B \)-space \( X \) with a basis, \( X_s \) is \( \gamma \)-complete if and only if it is \( \gamma \)-reflexive.
Proof. Every γ-reflexive space is obviously γ-complete. On the other hand, the γ-completeness of $X_s$ implies the boundedly completeness of the basis for $X$. Hence $X \cong C(X) = A(X_s)^*$ by Theorem 3.4, that is $X_s$ is γ-reflexive.

Corollary 3.6 [9, p. 143]. Let $X$ be a B-space which has a basis $\{x_n\}$ and let $Y = [y_n]$ be the closed linear subspace of $X^*$ spanned by the $y_n$, $y_n(x_j) = \delta_{n,j}$. Then $Y^*$ is isomorphic to the B-space of scalars

$$E = \left\{ \{b_n\} : \sup_{n} \left| \sum_{k \leq n} b_k x_k \right|_1 < \infty \right\}$$

where the norm is defined by $\|\{b_n\}\| = \sup_n \left| \sum_{k \leq n} b_k x_k \right|_1$.

Proof. This follows from our remarks made earlier and the fact that the γ-completion of $X_s$ in this case is $Y^* = A(X_s)^*$.

Corollary 3.7. Let $X$ be a B-space with a (monotone) shrinking Schauder decomposition $\{X_i\}$. Then $X_1^*$ is isomorphic (respectively isometrically isomorphic to) to $C(X)$ if and only if each $X_i$ is reflexive.

Proof. By [10, Corollary 3-5], $A(X_s) = X_1^*$ so that $A(X_s)^* = X_1^{**}$ and the conclusion now follows from Theorem 3.4.

We may remark that if each $X_i$ is of dimension 1, Corollary 3.7 reduces to a result of R. C. James (see [9, p. 143]).

Theorem 3.8. Let $(X, | |_1)$ be a B-space with a Schauder decomposition $\{X_i\}$. If $i$ is defined as in Theorem 3.2, then $i(X) = \{J(x_i)\}$, $\sum_j f(x_j)$ converges in $A(X_s)^*$]. Further $\{X_i\}$ is boundedly complete if and only if $i$ is bijective, that is, $i(X) = C(X)$.

Proof. For $x = \sum_j x_j$ in $X$, $i(x) = \{J(x_j)\}$ and $\sum_j f(x_j)$ converges in $A(X_s)^*$, hence in $A(X_s)^*$. Conversely, if $\{J(y_j)\} \in C(X)$ such that $\sum_j f(y_j)$ converges, then $\sum_j f(y_j) \in \bigcup_{j} f(X_j) = f(X)$, where $[\bigcup]$ denotes closed linear span. Thus for some $y$ in $X$, $f(y) = \sum_j f(y_j)$ and $i(y) = \{f(y_j)\}$.

If $\{X_i\}$ is boundedly complete for $X$, then so is $\{f(X_i)\}$ for $f(X)$. Hence

$$\{f(x_j)\} \in C(X) \iff \sup_{n} \left| \sum_{j \leq n} f(x_j) \right|_1^{**} < \infty \iff \sum_j f(x_j) \text{ converges}$$

$$\iff \{f(x_j)\} \in i(X) \iff C(X) = i(X).$$

The following result was observed in [10].
Theorem 3.9. Let \( \{X_j\} \) be a monotone Schauder decomposition for a B-space \( X \). The canonical two-norm space \( X_s \) is \( \gamma \)-reflexive if and only if \( X_s \) is \( k \)-reflexive and \( \gamma \)-complete.

Proof. \( X_s \) is \( \gamma \)-reflexive if and only if \( J: X \rightarrow A(X_s)^* \) is 1-1 and onto is bijective and \( A(X_s)^* = C(X) \) if \( X_s \) is \( k \)-reflexive and \( \{X_j\} \) is boundedly complete by Theorems 3.4 and 3.8.

4.0 Pseudo-reflexivity. Let \( (X, \|\cdot\|) \) be a B-space and \( Y \) a closed linear subspace of \( X_s^* \). Following Singer [9], we shall say that \( X \) is \( Y \)-pseudo reflexive if the canonical map \( J \) from \( X \) into \( Y^* \) is a linear isomorphism onto \( Y^* \). If \( J \) is an isometry as well, \( X \) will be called \( Y \)-reflexive. Singer has shown [9, p. 140] that a necessary and sufficient condition for \( X \) to be \( Y \)-reflexive is that the closed unit ball \( S \) of \( X \) be complete for the topology \( \sigma(X, Y) \) and that \( Y \) be an \( X \)-total subspace of \( X_s^* \).

Let us observe that given a total, norming and closed linear subspace \( Y \) of \( X_s^* \), if there exists a norm \( \|\cdot\|_2 \) on \( X \) such that \( A(X_s) = Y \), then \( X \) is \( Y \)-reflexive if and only if \( X_s \) is \( \gamma \)-reflexive. In general, however, such a norm need not exist. If \( Y \) is separable, a suitable second norm may be defined on \( X \) such that for the resulting two-norm space \( X_s \) we have \( A(X_s) = Y \) [3, p. 124]. In this case we can give a different proof of the following theorem of Singer [9, p. 142]:

Theorem. Let \( (X, \|\cdot\|) \) be a B-space and \( Y \) a separable linear subspace of \( X_s^* \). Then \( X \) is \( Y \)-reflexive if and only if \( S \), the closed unit ball of \( X \), is sequentially complete for the topology \( \sigma(X, Y) \) and \( Y \) is an \( X \)-total subspace of \( X_s^* \).

Proof. The necessity is clear and it is also obvious that \( Y \) must be norming. On the other hand, to show that these conditions are sufficient, let \( \|x\|_2 = \Sigma_n |f_n(x)|/2^n \) where \( \{f_n\} \) is dense in \( \{f \in Y: \|f\|_1 = 1\} \). Then [3, p. 124], \( X_s \) is normal, \( \gamma \)-precompact and \( A(X_s) = Y \). Convergence in \( \|\cdot\|_2 \) being equivalent to convergence of each of the sequences \( \{f_n(\cdot)\} \), \( n = 1, 2, \ldots \), the sequential completeness of \( S \) for the topology \( \sigma(X, Y) \) implies that \( X_s \) is \( \gamma \)-complete. Hence \( X_s \) is \( \gamma \)-compact whence it is \( \gamma \)-reflexive [2, §5.2]. Hence \( X \) is \( Y \)-reflexive.

We now investigate the \( Y \)-reflexivity of a B-space \( (X, \|\cdot\|) \) with a Schauder decomposition \( \{X_j\} \), where \( Y = A(X_s) \) and \( X_s \) is the canonical two-norm space of \( X \). The following theorem characterizes the \( A(X_s) \)-reflexivity of \( X \).

Theorem 4.1. Let \( X \) be a B-space with a (monotone) Schauder decomposition \( \{X_s\} \) and let \( X_s \) be the canonical two-norm space of \( X \). The following are equivalent:

1. \( X \) is \( A(X_s) \)-pseudo reflexive (respectively \( A(X_s) \)-reflexive).
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(2) \( X_s \) is \( \gamma \)-semi reflexive (respectively \( \gamma \)-reflexive).

(3) \( \{X_j \}^* \) is boundedly complete and \( X_j \) is reflexive for each \( j \).

(4) \( A(X_s)^* = \sum_j f(X_j) = \sum_j A(k\cdot X_j) \).

(5) \( \{A(k\cdot X_j) \} \) is shrinking for \( A(X_j)^* \) and \( X_j \) is reflexive for each \( j \).

(6) \( X_s^* = \{X \}_{\text{reflexive}} \), where \( A(X_s)^\perp \) is the set \( \{F \in X_s^* : F(A(X_s)) = 0 \} \).

Proof. (1) \( \Rightarrow \) (2) by definition, (2) \( \iff \) (3) by Theorems 3.9, [10, Theorems 3.6, 4.7]. On the other hand \( X_s \) is \( \gamma \)-reflexive \( \iff \) \( A(X_s)^* = f(X) = \sum_j f(X_j) \subseteq \sum_j A(k\cdot X_j) \subseteq A(X_s)^* \) whence (2) \( \iff \) (4). Furthermore, (4) \( \iff \) \( A(X_s)^* = \sum_j A(k\cdot X_j) \) and \( f(X_j) = A(k\cdot X_j) \) for every \( j \) and this is equivalent to (5). Finally, the equivalence of (1) and (6) is a special case of the following theorem.

Theorem 4.2. Let \( X_s = (X, ||_1, ||_2) \) be a normal two-norm space satisfying \( (n_0) \) where \( ||_2 \) is a \( B^*_2 \)-norm. Then \( X_s \) is \( \gamma \)-reflexive if and only if \( X_s^* = f(X) \bigoplus A(X_s)^\perp \), where \( A(X_s)^\perp \) is the annihilator of \( A(X_s) \) in \( X_s^* \).

Proof. If \( X_s \) is \( \gamma \)-reflexive, then \( (A(X_s), ||_1^*) = f(X) \cong X \). Hence \( X_s^* \) is isometrically isomorphic to the third conjugate of \( A(X_s) \). Hence by a theorem of Diximier (see for instance [4, p. 426]), the projection

\[ \pi : X_s^* \to f(X) \]

defined by \( \pi(F) = F| f(X) \) for \( F \in X_s^* \) is continuous with norm 1 and kernel \( A(X_s)^\perp \). Hence \( X_s^* = f(X) \bigoplus A(X_s)^\perp \).

Conversely, since \( X_s \) satisfies \( (n_0) \), \( A(X_s) \) is a closed subspace of \( X_s^* \). Therefore, given \( f \in A(X_s)^* \), by the Hahn-Banach theorem there exists \( F \in X_s^* \) with the same norm as that of \( f \) and such that \( F| A(X_s) = f \). Hence there exist \( x \in X \) and \( g \in A(X_s)^\perp \) such that \( F = f(x) + g \). Now for any \( \xi \in A(X_s) \) we have \( F(\xi) = f(x)(\xi) \), that is, \( f(\xi) = f(x)(\xi) \). Thus \( f \equiv f(x) \) on \( A(X_s) \) so that we may conclude \( A(X_s)^* \subseteq f(X) \). Since the other inclusion is obvious, we have \( A(X_s)^* = f(X) \), that is \( X_s \) is \( \gamma \)-reflexive.

5.0 Direct sum of \( B \)-spaces. We now consider \( B \)-spaces \( X \) which arise as a countable direct sum of other \( B \)-spaces \( (X_i) \). In our case the structure of \( X \) and its norm will be determined by an underlying space \( B \), a \( BK \) space. Many sequence spaces may be considered as examples of such spaces. Several such spaces have also been used as counterexample spaces by many authors.

The spaces \( X_i \) may be considered as imbedded in \( X \), hence treated as subspaces of \( X \). In general, they do not form a decomposition of \( X \) for norm convergence. Nevertheless, each \( x \) in \( X \) shall correspond to a unique sequence \( \{x_n \} \), \( x_n \in X_i \). Also \( \{X_i \} \) will form a 'generalized decomposition' of \( X \) in the sense \( \bigcup_i P_k(X_i) \) shall be \( X \)-total in \( X^* \), where \( P_k : X \to X_k \). We shall see that a natural two-norm space \( X_s \) may be defined as before and the usual arguments of two-norm
spaces in Schauder decompositions adapted to spaces of this kind.

As an example, consider the space \((\mathbb{R}, \| \cdot \|)\). Here each \(X_n = \mathbb{R}\) and the space \(B\) is \((\mathbb{R}, \| \cdot \|)\) itself. The vectors \((e_n)\) form a generalized basis of \((\mathbb{R})\). A natural extension of the definition of boundedly complete bases shows that \((e_n)\) is boundedly complete for \((\mathbb{R})\). Note also that the associated two-norm space \((\mathbb{R}, \| \cdot \|)\) is \(\gamma\)-complete. We shall observe later that this is a special case of the analogue of [10, Theorem 3.6].

We begin with

**Definition 5.1.** A \(BK\) space \((B, \| \cdot \|_B)\) is a Banach space of real sequences such that \(\|a_n\|_B \geq \sum_n |a_n|/(2^n(1 + |a_n|))\) for elements \(|a_n\|_B \) in \(B\). The space \(B\) is called normal if for any two sequences \(|a_n|\) and \(|b_n|\), \(|a_n| \leq |b_n|\) and \(|b_n| \in B\) \(\Rightarrow |a_n| \in B\). We say \(B\) is ordered if for any two elements \(|a_n|, |b_n| \in B\) with \(|a_n| \leq |b_n|\), we have \(\|a_n\|_B \leq |b_n|_B\).

The above definition is equivalent to the usual definition of a \(BK\) space since it implies (and is implied by) the fact that the coordinate functionals are continuous.

All \(BK\) spaces \(B\) considered in this paper are assumed to have the following properties:

1. \(B\) is ordered and normal,
2. \(B\) contains the unit vectors \(|e_n| = \delta_{n,1}\) and \(|e_n|_B = 1\) for all \(n\), and
3. if \(|a_n| \in B\), then \(|a|_B = \sup_n |\|a\|_j|e_{jn}|_B\) where \(e_{jn} = 1\) for \(j \leq n\), = 0 for \(j > n\).

This last postulate has the advantage of making \(\| \cdot \|_B\) "monotone". In most cases of interest, the natural norm on the \(BK\) space is either equal or equivalent to a norm introduced in the above manner.

**Definition 5.2.** Let \((X_n, \| \cdot \|_{n})\), \(n = 1, 2, \ldots\), be a sequence of \(B\)-spaces and \((B, \| \cdot \|_B)\) a \(BK\) space. By the direct sum with respect to \(B\) of \((X_n)\), we shall mean the set of all those sequences \(x = |x_n|\) with \(x_n \in X_n\) and such that \(|x_n| \in B\). This set will be denoted by \(B \Sigma_n X_n\), and when there is no cause for confusion about the underlying space \(B\), merely by \(\Sigma_n X_n\).

**Theorem 5.3.** Let \(X = B \Sigma_n X_n\) and for \(x = |x_n| \in X\), define \(\|x\| = \|\|x_n|\|_B\). Then \((X, \| \|)\) is a \(B\)-space.

**Proof.** We need only show that \((X, \| \|)\) is complete. Let \(|x_n|\) be a Cauchy sequence in \(X\) where \(x_n = \{x_n^{(j)}\}_{j=1}^\infty\). Then given \(\epsilon > 0\), \(\exists N(\epsilon)\) such that \(n, m > N\) implies

\[
\|x_n - x_m\| = \lim_{j \to \infty} \|x_n^{(j)} - x_m^{(j)}\|_B < \epsilon.
\]

Since \(B\) is ordered, for \(n, m > N\) and any \(j\),
\[ |x_n^{(j)} - x_m^{(j)}| \leq \|x_n^{(k)} - x_m^{(k)}|_{\delta_j, k} \|_B < \varepsilon. \]

Hence \( \{x_n^{(j)}\} \) is Cauchy in \( X_j \) for each \( j \), so that \( x_n^{(j)} \to x_0^{(j)} \in X_j \) uniformly for all \( j \). Since \( \{\|x_n^{(j)}\|_j\} \in B \) for each \( n \) and \( B \) is ordered, it follows that \( \{\|x_n^{(j)}\|\}_{n=1}^{\infty} \) is Cauchy in \( B \) and converges to \( \|x_0^{(j)}\|_j \in B \). Since \( B \) is complete, \( \{x_0^{(j)}\} \in X \). It is routine to show that \( x_n \) converges to \( \{x_0^{(j)}\} \) and this completes the proof.

Consider the subspace \( Y_n \subseteq X \) consisting of all elements of the form \( \sum n \delta_n \), \( \delta_n \) being the Kronecker \( \delta \). The map \( t_n \) from \( X_n \) onto \( Y_n \) defined by \( t_n(z) = z \delta_n \), \( z \in X_n \), is clearly an isometry. We shall, therefore, occasionally identify \( X_n \) and \( Y_n \) in the future and consider \( X_n \) as a subspace of \( X \).

**Definition 5.4.** Let \( X = B \sum_n X_n \). The canonical two-norm space of \( X \) is the two-norm space \( (X, \| \|, \| \|_2) \) where, for \( x = \sum x_n \in X \), \( \|x\|_2 = \sum_n \|x_n\|/2^n \).

**Theorem 5.5.** Let \( X_s \) be the canonical two-norm space of \( X = B \sum_n X_n \). Then \( X_s \) is normal and satisfies \( (n_0) \).

**Proof.** Let \( x_n \overset{n}{\to} \xi \) in \( X_s \) where \( x_n = \sum x_n \in X \), \( \xi = \xi^S \), \( x_n \in X_j \), \( j = 1, 2, \ldots \). For each \( p \),

\[ \|\xi_n\| = \left\| \sum |\xi_n^{(j)}|_j e_j \right\|_B \leq \lim \inf_n \|x_n\|, \]

It follows that \( \|\xi\| \leq \lim \inf_n \|x_n\| \) showing that \( X_s \) is normal. That \( X_s \) satisfies \( (n_0) \) is clear since, for any \( x \in X_s \), \( \|x\|_j \leq \|x\|_2 \) (\( B \) is ordered) whence \( \|x\|_2 \leq \|x\| \).

An immediate corollary of the above theorem is that the canonical map \( J : X \to A(X_s)^* \) is an isometry. In what follows we write \( X_s^* \) for \( (X, \| \|)^* \). We shall have no occasion to consider the space \( (X_s, \| \|_1)^* \) and once again the reader is asked not to confuse the latter space for \( X_s^* \).

**Definition 5.6.** Let \( X = B \sum_n X_n \). The sequence \( \{X_n\} \) is said to be boundedly complete if for any sequence \( \{x_n\} \in X_n \), \( \sup_n \|x_n\|_1 = \infty \) implies \( \{x_n\} \in X \).
Definition 5.7. Let \( X = B - \sum_n X_n \) and let \( Z_n \) be the subspace of \( X \) consisting of sequences whose first \( n \) coordinates are zeros. For \( f \in X_1^* \) let \( |f|_{1,n}^* = \sup \{|f(x)| : x \in Z_n, \|x\| = 1\} \). Then \( (X_n) \) is said to be shrinking for \( f \in X_1^* \) if
\[
\lim_{n \to \infty} |f|_{1,n}^* = 0.
\]

In the special case when \( (Y_n) \) forms a Schauder decomposition of \( X \), the above definitions reduce to the usual definitions of boundedly completeness and the shrinking property. We also note that under this definition the unit vectors form a generalized boundedly complete basis for \( (m) \) and are shrinking for every element in \( l \). This is a special case of the following

Theorem 5.8. Let \( X = B - \sum_n X_n \). Then the sequence \( (X_n) \) is boundedly complete if and only if \( X_s \) is \( \gamma \)-complete. Further \( (X_n) \) is shrinking for \( f \in X_1^* \) if and only if \( f \in A(X_s) \).

The proof is similar to those of [10, Theorems 3.4, 3.6]. We indicate the lines of the proof of the second assertion leaving that of the first to the reader.

**Proof of second assertion.** Given \( \epsilon > 0 \) and \( f \in A(X_s) \) we can find \( \delta > 0 \) such that \( \|x\| \leq 1 \) and \( \|x\|_2 < \delta \) imply \( |f(x)| < \epsilon \). Choose \( N > 0 \) such that \( n > N \) implies \( \sum_{j=n}^{\infty} 2^{-j} < \delta \). Then for \( \xi = a_j \xi_j \) in \( Z_n \) with \( \|\xi\| = 1 \) we have \( \|\xi\|_2 < \delta \) so that \( |f(\xi)| < \epsilon \). This shows \( |f|_{1,n}^* < \epsilon \) for \( n > N \).

For the other part, we identify \( x_n, \in X \), with \( x_n, \in X_1 \), in \( X, j = 1, 2, \ldots \). Let \( f \in X_1^*, x_n \to 0 (y) \) in \( X_s \), and suppose \( \|x_n\| \leq 1 \). Find \( N > 0 \) such that \( \|f\|_{1,N}^* < \epsilon/2 \), \( \epsilon > 0 \) being arbitrary. There exists \( M \) such that \( |f(x_n)| < \epsilon/2N \) whenever \( n > M \) and \( 1 \leq j \leq N \). Clearly for \( n > M \) and \( 1 \leq j \leq N \) we have
\[
|f(x_n)| \leq \sum_{j=1}^{N} |f(x_n, j)| + \|f(x_n - \sum_{j=1}^{N} x_n, j)| < N \cdot \epsilon / 2N + \epsilon / 2 = \epsilon
\]
showing that \( f \) is \( \gamma \)-linear. This completes the proof.

For \( x = \{x_n\} \in X \), the map \( S_n : X \to X \) defined by \( S_n(x) = \{x, \epsilon_{jn}\} \) is clearly continuous. Hence the projection operator \( P_n : X \to Y_n, P_n(x) = \{x, \delta_{jn}\} \) is also continuous. Since \( P_n(X_1^*) \subseteq A(X_s) \) trivially and \( A(X_s) \) is closed, \( \bigoplus_{k=1}^{\infty} P_k(X_k^*) \subseteq A(X_s) \). On the other hand, for any \( f \) in \( A(X_s) \), \( |f|_{1,n}^* \to 0 \) by the last theorem so that \( \|f - \sum_{k \leq n} P_k(f)|_{1,n}^* \to 0 \) as \( n \to \infty \). From these considerations we get

**Theorem 5.9.** Let \( X = B - \sum_n X_n, \) its canonical two-norm space. Then \( \{P_k(X_k^*)\} \) is a Schauder decomposition of \( A(X_s) \).

6.0 The \( \gamma \)-completion of \( X_s, X = B - \sum_n X_n \). As in the case of \( B \)-spaces with Schauder decompositions, the \( \gamma \)-completion of the canonical two-norm space \( X_s \) where \( X = B - \sum_n X_n \) may be constructed. One easily verifies that in this case
the space $C(X)$ may be identified with the space $B-\Sigma_n' X_n$ of all sequences $\{x_n\}$, $x_n \in X_n$, such that
\[
\forall \{x_n\} = \sup_n \|x_n\|_1 \leq 1
\]
is finite. The norm in the $B$-space $C(X)$ is $N()$. It is also possible to describe
the space $C(X)$ in a different way.

The $F$-space $(s, \| \cdot \|_s)$ of all scalar sequences with the Fréchet metric $\| \cdot \|_s$ has the unit vectors $\{e_n\}$ for a basis. Since $B$ is dense in $s$, $(B, \| \cdot \|_s)^*$ is the
linear span $\{e_n\}$. It is clear that $B_s = (B, \| \cdot \|_s)$ is normal ($\| \cdot \|_B$ being 'monotone' so that $A(B_s)$ is the closure of $\{e_n\}$ in $(B, \| \cdot \|_B)^*$ [2, p. 277]. Hence $\{e_n\}$
is a basis for $A(B_s)$ and a weak-* basis for $A(B_s)^*$. It is easily verified that
$A(B_s)^*$ is an ordered, normal $BK$ space consisting of scalar sequences $\{a_k\}$ with
$\|a_k\|_0 = \sup_n \|a_k e_n\|_B$ finite. But this is precisely the space $C(B)$ so that
$C(B) = A(B_s)^*, \| \cdot \|_0$ being its norm. We now have

**Theorem 6.1.** $B-\Sigma_n' X_n = C(B)-\Sigma_n X_n$.

**Proof.** We need only show that the set on the right is contained in the one
on the left. The normality of $B_s$ shows that the canonical map $B \rightarrow A(B_s)^* = $ $C(B)$ is an isometry. Let $\| \cdot \|_B$ denote the norm in $C(B)-\Sigma_n X_n$ and suppose $\{x_k\}$
is an element of it. Then,
\[
\|\|x_k e_n\|_B = \|\|x_k e_n\|_{C(B)} = \|\|x_k e_n\|_B = N(\{x_k e_n\})
\]
showing that $\{x_k\} \in B-\Sigma_n' X_n$ and completing the proof.

7.0 The $\alpha$-duals. Given the space $X = B-\Sigma_n X_n$, we shall call the canonical
two-norm space of the space $A(X)$ as the $\alpha$-dual of $X_s$ and denote it by $\alpha-X_s$.
Higher $\alpha$-duals are defined by induction. We note that $\alpha^2-X_s$ coincides with the
$k$-dual (see §6) of $\alpha-X_s$. In the special case when $(Y_n)$ forms a Schauder decom-
position of $X$, the $\alpha$-duals of $X_s$ are identical with its $k$-duals.

It was shown in §6 that for any $BK$ space $B$, $A(B_s)$ has the unit vectors
$\{e_k\}$ for a basis. Thus one may define the $\alpha$-duals of $B_s$ (called $T(B_s), T^2(B_s)$ etc., in [6]). It was shown in [6] that in general $\alpha^2-B_s$ is isometrically imbedded in $B_s$ and
that this isometry is onto $B_s$ if and only if $B$ has $\{e_k\}$ for a basis.

We shall show here that these results may be extended to our present setting.

For $X = B-\Sigma_n X_n$, we call $X_s$ "$\alpha$-reflexive" if $\alpha^2-X_s$ is isometrically isomor-
phic to $X_s$ under the canonical map. We begin by showing

**Theorem 7.1.** Let $X = B-\Sigma_n X_n$. Then, if $X_s$ is reflexive for each $j$, $J^{-1}:
\alpha^2-X_s \longrightarrow X_s$, where $J$ denotes the canonical map from $X_s$ into $A(X_s)^*$.
Proof. Let \( \{A(X_s)_k, p_k^*\} \) be the Schauder decomposition of \( A(X_s)_k \), \( A(X_s)_k^*, p_k^* \) the Schauder decomposition of \( A(\alpha-X_s)_k \) in the norm topology of \( A(X_s)_k^* \). By the reflexivity of \( X_j \) for each \( j \), it follows that

\[
A(\alpha-X_s)_k = \left[ \bigcup_j A(X_s)_j^* \right] = \left[ \bigcup_j J(Y_j) \right].
\]

Since \( J \) is an isometry from \( X \) into \( A(X_s)_k^* \), \( J^{-1}A(\alpha-X_s)_k = \left[ \bigcup_j Y_j \right] \subseteq X \), the closure in \( ] \) being with respect to the norm in \( X \). This completes the proof.

Theorem 7.2. Let \( X = B - \sum_n X_n \). If \( B \) is \( \alpha \)-reflexive then \( (X_n) \) is a Schauder decomposition of \( X \) in the sense that \( X = \bigoplus \sum_n X_n \). Further if \( B \) is \( \alpha \)-reflexive, \( X_j \) is reflexive for each \( j \) if and only if \( X_j \) is \( \alpha \)-reflexive.

Proof. Let \( x = \{x_n\} \in X \), \( x_n \in X_n \). Let \( y_n = \{x_j \delta_{j,n}\} \). We shall show that \( \|x - \sum_{j \leq n} y_j\| \to 0 \). Indeed,

\[
\left\| x - \sum_{j \leq n} y_j \right\| = \sup_m \left\{ \sum_{j = n+1}^m \left\| x_j \right\| e_j \right\}_B \leq \sum_{j > n} \left\| x_j \right\| e_j \to 0
\]

since by the \( \alpha \)-reflexivity of \( B \), \( \{e_j\} \) is a basis for \( B \) and \( \{x_n\} \in X \Rightarrow \{x_n\} \in B \Rightarrow \sum_n \left\| x_n \right\| e_n \) converges in \( B \).

To show the other part, observe that \( \{Y_n\} \) is a Schauder decomposition of \( X \) implies that \( \alpha \)-reflexivity coincides with \( k \)-reflexivity. An application of [10, Theorem 4.7] completes the proof.

The following theorem characterizes the \( \alpha \)-reflexivity of \( X_s \).

Theorem 7.3. Let \( X = B - \sum_n X_n \). Then \( X_s \) is \( \alpha \)-reflexive if and only if \( (X_n) \) forms a Schauder decomposition of \( X \) and \( X_s \) is reflexive for each \( n \).

Proof. If \( X_s \) is \( \alpha \)-reflexive, \( J(X) = A(\alpha-X_s)_k \). Since \( A(\alpha-X_s)_k \) has a Schauder decomposition \( \{A(X_s)_k, p_k^*\} \), it follows that \( A(X_s)_k^* = p_k^*(J(X)) \) and \( \{p_k^*(J(X)), p_k^*\} \) forms a Schauder decomposition for \( J(X) \). But for any \( k \), \( p_k^*(J(X)) = J(Y_k^*) \). For, if \( f = \sum_k f_k \in A(X_s)_k \), \( x = \{x_k\} \in X \),

\[
p_k^*(J(x))f = J(x)p_k^*(f) = f_k(x) = f_k(y_k)
\]

so that \( p_k^*(J(x)) = J(y_k^*), \ y_k^* = \{x_j \delta_{k,j}\} \), whence \( p_k^*(J(x)) \subseteq J(Y_k^*) \). Since \( p_k^*(J(y_k^*)) = J(y_k^*) \), the other inclusion is clear and our assertion is proved. It follows then that \( A(X_s)_k^* = J(Y_k^* \} \) for every \( k \), whence \( Y_k^* \) is reflexive for every \( k \), and \( J(X) = \bigoplus \sum_k J(Y_k^*) \), that is, \( X = \bigoplus \sum_k Y_k^* \).
The converse follows from [10, Theorem 4.7] and the fact that if $X = \bigoplus \Sigma_k Y_k$, then $\alpha$-reflexivity coincides with $k$-reflexivity. This completes the proof.

**Corollary 7.4.** Let $X = B-\Sigma_n X_n$. If $X_s$ is $\gamma$-complete and $\alpha$-reflexive, then $X_s$ is $\gamma$-reflexive.

Let us remark that the converse to the above corollary is false. One may take $X = (m)$. Here $m_s$ is $\gamma$-reflexive but not $\alpha$-reflexive. However, we have the following theorem.

**Theorem 7.5 (cf. [8]).** Let $X = B-\Sigma_n X_n$. The following are equivalent:

1. $X$ is reflexive.
2. $X_s$ is $\alpha$-reflexive, $(X_n)$ is boundedly complete and $(X_n)$ is shrinking for $(X, \| \|)*$.
3. $X_n$ is reflexive for each $n$, $(X_n)$ is boundedly complete and $(X_n)$ is shrinking for $(X, \| \|)$.

**Proof.** $X$ is reflexive if and only if $X_s$ is $\gamma$-reflexive and saturated [2, Theorem 3.7]. Recall that $X_s$ is saturated if $A(X_s) = (X, \| \|)*$. The equivalence of (1) and (3) now follows from Theorem 6.4 and Theorem 5.8. That (2) implies (1) is clear since $X = \bigoplus \Sigma_n X_n$ in this case, $\alpha$-reflexivity is identical with $k$-reflexivity and the conclusion follows from [8, Theorem 2]. It remains to show that (1) implies (2).

The reflexivity of $X$ immediately implies the reflexivity of $Y_n$, hence that of $X_n$, for each $n$. As observed before, $X_s$ is $\gamma$-reflexive and saturated so that $(X_n)$ is boundedly complete and $(X_n)$ is shrinking for $(X, \| \|)*$. To complete the proof, we must show that $X_s$ is $\alpha$-reflexive. Since $X$ is reflexive, $X_n$ is reflexive for each $n$ and $A(X_s) = (X, \| \|)*$, we have

$$J(X) = (X, \| \|)** = A(X_s)^* = \sum_k p_k^*(A(X_s)^*) = \sum_k J(Y_k)$$

where $\Sigma^*$ denotes convergence in the weak-* topology of $(X, \| \|)**$. This means that $(Y_k)$ is a weak Schauder decomposition, and hence [7, I.20] a Schauder decomposition of $X$ in the norm topology. Hence $X_s$ is $\alpha$-reflexive by Theorem 7.3 completing the proof.

**Corollary 7.6.** If $X = B-\Sigma_n X_n$, where $(X_n)$ does not form a Schauder decomposition of $X$, then $X$ is not norm-reflexive. In particular, for any sequence $(X_n)$ of $B$-spaces, $m-\Sigma_n X_n$ is not reflexive.

**8.0 Use as counterexamples.** We conclude this paper with a remark on the usefulness of the spaces $X = B-\Sigma_n X_n$ as counterexamples. Day(1) gives examples of reflexive $B$-spaces not isomorphic to uniformly convex spaces. Here one takes $B = $
$l^p$, $1 < p < \infty$, and the spaces $X_n$ are finite dimensional spaces. If we take $B = l$ and $X_n = c_0$ for each $n$ (all over $\mathbb{R}$), we obtain [10, Remark after Theorem 5.3] an example of a $B$-space with a boundedly complete Schauder decomposition but not isometrically isomorphic to a dual space (cf. [8]). Incidentally, this example also illustrates Theorem 7.2 since $l_\infty$ is known to be $\alpha$-reflexive. If one takes $B = l$ and $X_n = m$ for each $n$, one obtains an example of a nonseparable $B$-space with a Schauder decomposition. Finally, by taking $B = m$, $X_n = c_0$ for each $n$, one obtains [6, p. 113] an example of a $B$-space with a countable determining set (that is a countable set $D = \{f \in X : ||f||_1 \leq 1\}$ such that $||x|| = \sup \{||f(x)|| : f \in D\}$, $||\cdot||$ and $||\cdot||_1$ being the norms in the space and its conjugate respectively) which is neither separable nor the dual of a separable space. For other counterexamples concerning two-norm spaces, the reader is referred to [6].

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