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ON THE DUNFORD-PETTIS PROPERTY OF FUNCTION MODULES OF ABSTRACT L-SPACES

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The main result of this note states that a function module of Banach spaces has the Dunford-Pettis Property, provided that all summands are spaces of the form $L_1(\mu)$. As a corollary we obtain that every injective Banach lattice has the Dunford-Pettis Property. Another corollary states that certain spaces of compact operators have the Dunford-Pettis Property.

1. Introduction. In 1940, Nelson Dunford and Bill Pettis published their now classical result that weakly compact operators defined on $L_1(\mu)$ are completely continuous. Ten years later Grothendieck showed that the space of real-valued continuous functions on any compact topological space enjoys the same property which today is called the Dunford-Pettis Property. Specifically:

DEFINITION. Let E be a Banach space and assume that every weakly compact operator $T: E \to F$, F a Banach space, sends weakly compact subsets of E into norm compact subsets of F. Then we say that E has the Dunford-Pettis Property.

Since the early 50's the Dunford-Pettis Property has attracted much attention in the theory of Banach spaces (see the survey article of J. Diestel [5] for the historical development). However, up to today it is not quite clear which Banach spaces have the Dunford-Pettis Property. Until one or two years ago, even the following question was unanswered:

Question. If X is a compact Hausdorff space and if E is a Banach space with the Dunford-Pettis Property, does the space of all vector valued continuous functions $C(X, E)$ also have the Dunford-Pettis Property?

In 1983, M. Talagrand [**18**] answered this question in the negative by constructing a Banach space E which had the Dunford-Pettis Property, but $C([0,1], E)$ did not have the Dunford-Pettis Property. However, for important classes of Banach spaces, the above question has a positive answer. This is for instance the case, if E is a Schur space (see I. Dobrakov [**6**]) or if E is a space of type $L_1(\mu)$ (see J. Bourgain [**2**]). (A Schur space is a Banach space in which every weakly convergent sequence is norm convergent.)

In this note, we will change the above question a little bit and consider function modules of Banach spaces instead of spaces of continuous functions with values in a fixed Banach space E. There are two reasons to do so:

(1) Function modules of Banach spaces contain, among other examples, spaces of continuous functions defined on a locally compact space vanishing at infinity, spaces of continuous functions equipped with a weighted norm, and Banach spaces of continuous vector fields on a differentiable manifold.

(2) Function modules are an important tool in the representation theory of C^*-algebras.

The major result of this note extends Bourgain's result on $C(X, L_1(\mu))$ in the following way: If all stalks of a function module are AL-spaces, then this function module has the Dunford-Pettis Property. The proof utilizes some properties of the local structure of function modules which are obtained in §3. An interesting corollary of the main result states that every injective Banach lattice (in the sense of [**3**]) is a Dunford-Pettis space.

Throughout this paper, we will follow the terminology of [**16**]. Especially, Banach spaces will be denoted by $E, F\ldots$, and their (topological) duals by E', etc. The letter X always denotes a compact Hausdorff space and the term 'compact' always includes the Hausdorff separation axiom. If E_i, $i \in I$, is a family of Banach spaces, then their l_∞-sum is denoted by $\prod_{i\in I} E_i$ and their l_1-sum is denoted by $\oplus_{i\in I} E_i$.

2. Notations. In this preliminary section, we will recall the definition of function modules of Banach spaces:

Let us suppose that we start with a compact Hausdorff space X and a family of Banach spaces $(E_x)_{x\in X}$. Assume further that we are given a closed linear subspace

$$E \subset \prod_{x\in X} E_x = \left\{(\sigma(x))_{x\in X} \colon \sigma(x) \in E_x \text{ for all } x \text{ and } \sup_{x\in X} \|\sigma(x)\| < \infty\right\}$$

such that the following conditions are satisfied:

(a) For every $x \in X$ and every $a \in E_x$ there exists an element $\sigma \in E$ such that $\sigma(x) = \alpha$.

(b) The mapping $x \mapsto \|\sigma(x)\|: X \to \Re$ is upper semicontinuous for every $\sigma \in E$.

(c) If $\sigma \in E$ and a continuous real-valued function $f \in C(X)$ are given, then $f\sigma$ belongs to E, where $f\sigma$ is defined by $(f\sigma)(x) = f(x)\sigma(x)$ for all $x \in X$.

Then E is called a *function module over X*. For a given $x \in X$, the Banach space E_x is called the *stalk* over x.

Banach spaces E which satisfy these conditions are also called *upper semicontinuous function spaces* (see **[4]**) *or continuous sums of the Banach spaces* E_x, $x \in X$ (see R. Godement **[10]**, I. Kaplansky **[12]**, and Gelfand and Naimark **[15]**). They also occur as spaces of sections in bundles of Banach spaces (see **[9]** for the details of this last equivalence). Our notation is the one of E. Behrends **[1]**.

Function modules E are $C(X)$-convex $C(X)$-modules in the following sense: Given elements $\sigma, \tau \in E$ such that $\|\sigma\|$, $\|\tau\| \leq 1$, and given a continuous function $f \in C(X)$ such that $0 \leq f \leq 1$, then $\|f\sigma + (1-f)\tau\| \leq 1$. This generalizes to convex combinations of more than two elements in the following way (see **[9**, 7.14] for details):

Given $\sigma_i \in E$ $1 \leq i \leq n$, and a partition of unity $(f_i)_{1 \leq i \leq n}$ of X, then

$$\left\| \sum_{i=1}^{n} f_i \sigma_i \right\| \leq \max_{1 \leq i \leq n} \|\sigma_i\|.$$

If all the stalks of a function module E are AL-spaces, i.e. spaces of the form $L_1(\mu)$ for a positive measure μ, then E is called a function module of AL-spaces. Function modules of AL-spaces are important in the representation theory of injective Banach lattices (see **[3]** for the definition of injective Banach lattices). Every injective Banach lattice may be represented as a function module of AL-spaces. Furthermore, it is possible to characterize exactly those function modules of AL-spaces which in fact yield injective Banach lattices (see **[7]** and **[11]**).

Another important class of Banach spaces which can be represented as function modules are Grothendieck's G-spaces. Recall that a closed linear subspace $G \subset C(K)$, K compact, is called a *G-space*, provided that there are triples $(x_i, y_i, r_i) \in K \times K \times \Re$, $i \in I$, such that $G = \{f \in C(K): f(x_i) = r_i f(y_i) \text{ for all } i \in I\}$. In order to avoid technical difficulties, we will assume that 0 is not in the weak $*$-closure of the extreme points of the dual unit ball of G. In this case we have

2.1. THEOREM (*Möller* [**14**]). *Let G be a G-space and assume that 0 is not an element of the weak $*$-closure of the extreme points of the dual unit ball of G. Then there exists a function module E over a compact space X such that G is isometrically isomorphic to E. Moreover, all the stalks of this function module are one-dimensional.*

The *proof* of this result follows from [**14**, 4.1], [**14**, 3.6(vi)], and the fact that for compact spaces X the notions of sections in bundles and function modules are equivalent. □

3. The local structure of bundles of AL-spaces. In this section we will be dealing with finite dimensional subspaces of function modules of AL-spaces over compact spaces X. Let E be such a function module and let $U \subset E$ be a finite dimensional subspace. For every given $\varepsilon > 0$ we will construct a finite dimensional subspace V such that

(i) $U \subset V$,

(ii) There are finite dimensional AL-spaces $l_1(n_1), \ldots, l_1(n_m)$ having the property that the Banach-Mazur distance between V and the l_∞-sum $l_1(n_1) \times \cdots \times l_1(n_m)$ is less than $1 + \varepsilon$.

We need a technical notation:

If E is a function module over X, if $\delta \geq 0$, and if $F \subset E$, then we let

$$\operatorname{peak}_\delta(F) = \{x \in X : \|\sigma\| - \delta \leq \|\sigma(x)\| \text{ for all } \sigma \in F\}.$$

Note that the upper semicontinuity of the norm implies that $\operatorname{peak}_\delta(F)$ is closed in X.

3.1. LEMMA. *Let $\delta > 0$ be a positive real number, let E be a function module over a compact base space X, and let $\sigma_{i,j} \in E$, $1 \leq i \leq n$ and $1 \leq j \leq n_i$, be a finite set of elements such that $|\,\|\sigma_{i,j}\| - 1| \leq \delta$ for all i, j. Furthermore, let $U_1, \ldots, U_n \subset X$ be a (finite) open cover of X such that condition $(*)$ is satisfied:*

$(*)$ *For every $1 \leq i \leq n$ there exist pairwise different elements*

$$x_i \in \operatorname{peak}_\delta(\{\sigma_{i,j} : 1 \leq j \leq n_i\}) \cap U_i$$

such that

$$\left\| \sum_{j=1}^{n_i} r_j \sigma_{i,j}(x_i) \right\| = \sum_{j=1}^{n_i} |r_j| \, \|\sigma_{i,j}(x_i)\|$$

holds for every choice of real numbers $r_j \in \mathfrak{R}$, $1 \leq j \leq n_i$.

Then there exists a partition of unity subordinated to the open cover $(U_i)_{1\le i\le n}$, *say* $(f_i)_{1\le i\le n}$, *such that the Banach-Mazur distance between the linear span of* $\{f_i\sigma_{i,j}\colon 1\le i\le n,\ 1\le j\le n_i\}$ *and the* l_∞*-sum* $\prod_{i=1}^n l_1(n_i)$ *is less than or equal to* $(1+\delta)/(1-2\delta)$.

Proof. Every function module E is a $C(X)$-convex $C(X)$-module. Hence for every choice of real numbers $(r_{i,j})_{1\le j\le n_i,1\le i\le n}$ and every partition of unit $(f_i)_{1\le i\le n}$ we have

$$(1)\qquad \left\|\sum_{i=1}^{n}\sum_{j=1}^{n_i} r_{i,j}f_i\sigma_{i,j}\right\| = \left\|\sum_{i=1}^{n} f_i\left(\sum_{j=1}^{n_i} r_{i,j}\sigma_{i,j}\right)\right\|$$
$$\le \max_{1\le i\le n}\left\|\sum_{j=1}^{n_i} r_{i,j}\sigma_{i,j}\right\| \le (1-\delta)\max_{1\le i\le n}\sum_{j=1}^{n_i}|r_{i,j}|.$$

We now choose a special partition of unity: For every $1\le i\le n$ let

$$V_i = U_i\setminus\{x_j\colon 1\le j\le n, j\ne i\}.$$

Then, since the x_i are pairwise distinct and therefore $x_i\in V_i$, the V_i's are still an open cover of X. Let $(f_i)_{1\le i\le n}$ be any partition of unity subordinate to $(V_i)_{1\le i\le n}$. Further, since for every i we have $\sum_{j=1}^n f_j(x_i)=1$ and $x_i\notin V_j$ for $j\ne i$, we conclude that $f_i(x_i)=1$. For every $1\le k\le n$ we obtain the inequality

$$\left\|\sum_{i=1}^{n}\sum_{j=1}^{n_i} r_{i,j}f_i\sigma_{i,j}\right\| \ge \left\|\left(\sum_{i=1}^{n} f_i\left(\sum_{j=1}^{n_i} r_{i,j}\sigma_{i,j}\right)\right)(x_k)\right\|$$
$$= \left\|\sum_{j=1}^{n_k} r_{k,j}\sigma_{k,j}(x_k)\right\| = \sum_{j=1}^{n_k}|r_{k,j}|\,\|\sigma_{k,j}(x_k)\|$$
$$\ge \sum_{j=1}^{n_k}|r_{k,j}|\big(\|\sigma_{k,j}\|-\delta\big) \ge (1-2\delta)\sum_{j=1}^{n_k}|r_{k,j}|$$

and therefore

$$(2)\qquad \left\|\sum_{i=1}^{n}\sum_{j=1}^{n_i} r_{i,j}f_i\sigma_{i,j}\right\| \ge (1-2\delta)\max_{1\le i\le n}\sum_{j=1}^{n_i}|r_{i,j}|.$$

Define a linear operator T by

$$T\colon \prod_{i=1}^{n} l_1(n_i) \to \langle f_i\sigma_{i,j}\colon 1\le i\le n, 1\le j\le n_i\rangle$$
$$\times\,(r_{i,1},\dots,r_{i,n_i})_{1\le i\le n} \mapsto \sum_{i=1}^{n}\sum_{j=1}^{n_i} r_{i,j}f_i\sigma_{i,j}.$$

Then equation (1) implies that $\|T\| \leq (1 + \delta)$, whereas the second equation yields that $\|T^{-1}\| \leq 1/(1 - 2\delta)$. Hence the Banach-Mazur distance between the linear span of $\{ f_i\sigma_{i,j}: 1 \leq i \leq n, 1 \leq j \leq n_i\}$ and $\prod_{i=1}^{n} l_1(n_i)$ is less than or equal to $(1 + \delta)/(1 - 2\delta)$. □

Another notation: If $G \subset E$ is a linear subspace of a function module E over X, then we define $G_x = \{\sigma(x): \sigma \in G\}$. Note that G_x is a linear subspace of the stalk E_x.

3.2. LEMMA. *Let E be a function module of AL-spaces with base space X and let $G \subset E$ be a finite dimensional subspace. Let $\sigma_1,\ldots,\sigma_m \in G$ be a base of G consisting of elements of norm 1. Then for every $\varepsilon > 0$ there exists a finite dimensional subspace $H \subset E$ such that*

(i) *For every element of the base σ_k there is an element $\gamma_k \in H$ such that $\|\gamma_k\| = 1$ and $\|\sigma_k - \gamma_k\| \leq \varepsilon$.*

(ii) *The Banach-Mazur distance between H and a Banach space of the form $\prod_{i=1}^{n} l_1(n_i)$ is less than or equal to $1 + \varepsilon$.*

Proof. Choose $\delta > 0$ such that $2\delta < \varepsilon$ and $(1 + \delta)/(1 - 2\delta) < 1 + \varepsilon$. For every $x \in X$ consider G_x. Since the stalk E_x is an AL-space, there exists a finite dimensional subspace $V_x \subset E_x$ such that

(a) V_x is isometrically isomorphic to a space of the form $l_1(x_n)$.

(b) For every σ_k there exists an element of $\alpha_k \in V_x$ such that $\|\sigma_k(x) - \alpha_k\| < \delta$.

Let $\sigma_{x,1},\ldots,\sigma_{x,n_x} \in E$ be chosen such that the $\sigma_{x,k}(x) \in V_x$ correspond to the unit vector base in $V_x \cong l_1(n_x)$. In this case we have

(c) $\|\sum_{j=1}^{n_x} r_j\sigma_{x,j}(x)\| = \sum_{j=1}^{n_x} |r_j|\,\|\sigma_{x,j}(x)\|$ for every choice of real numbers $r_j \in \mathfrak{R}$, $1 \leq j \leq n_x$.

Moreover, since $\|\sigma_{x,j}(x)\| = 1$, we can find an open neighborhood $U \subset X$ of x such that $\|(\sigma)_{x,j}(y)\| < 1 + \delta$ for every $y \in U$. Pick a continuous function $f: X \to \mathfrak{R}$ which takes its values in the unit interval, is equal to 0 off the open set U, and equal to 1 at x. Then we have $|\,\|f\sigma_{x,j}\| - 1| \leq \delta$ and $(f\sigma_{x,j})(x) = \sigma_{x,j}(x)$. Hence, by passing from $\sigma_{x,j}$'s to $f\sigma_{x,j}$'s if necessary, we may assume that

(d) $|\,\|\sigma_{x,j}\| - 1| \leq \delta$ and $x \in \operatorname{peak}_\sigma(\sigma_{x,j})$ for all $1 \leq j \leq n_x$.

Let V^x be the linear span of the $\sigma_{x,j}$, $1 \leq j \leq n_x$. Then $(V^x)_x = V_x$. Hence, by statement (b) above, for every $k \in \{1,\ldots,m\}$ there is an element $\gamma_{x,k} \in V^x$ such that $\|\sigma_k(x) - \gamma_{x,k}(x)\| < \delta$. Using the upper semicontinuity of the norm function again, we can find an open neighborhood U_x of x such that

(e) $\|\sigma_k(y) - \gamma_{x,k}(y)\| < \delta$ for all $y \in U_x$ and all $k \in \{1,\ldots,m\}$.

Clearly, the open sets U_x, $x \in X$, cover X. Hence there are finitely many pairwise distinct elements $x_1, \ldots, x_n \in X$ such that $X = U_{x_1} \cup \cdots \cup U_{x_n}$. Define

$$U_i = U_{x_i} \quad \text{for all } 1 \leq i \leq n,$$
$$n_i = n_{x_i},$$
$$\sigma_{i,j} = \sigma_{x_i,j} \quad \text{for all } 1 \leq i \leq n, 1 \leq j \leq n_i.$$

Then, by (c) and (d), the conditions of Lemma (3.1) are satisfied. Pick a partition of unity $(f_i)_i$ subordinate to the U_i as promised in (3.1) and let H be the linear span of $\{f_i\sigma_{i,j}\colon 1 \leq i \leq n,\ 1 \leq j \leq n_i\}$. Then the Banach-Mazur distance between H and the m-product $\prod_{i=1}^n l_1(n_i)$ will be less than or equal to $(1+\delta)/(1-2\delta) < 1+\varepsilon$.

It remains to construct the elements $\gamma_k \in H$: Define elements $\tau_k \in H$ by

$$\tau_k = \sum_{i=1}^n f_i \gamma_{x_i,k}.$$

From (e) and the fact that the support of the function f_i is contained in $U_i = U_{x_i}$ we conclude that

$$\begin{aligned}\|\sigma_k - \tau_k\| &= \left\| \sum_{i=1}^n f_i(\sigma_k - \gamma_{x_i,k}) \right\| \\ &= \sup_{y\in X} \left\| \sum_{i=1}^n f_i(y)\big(\sigma_k(y) - \gamma_{x_i,k}(y)\big) \right\| \\ &\leq \sup_{y\in X} \sum_{i=1}^n f_i(y)\delta \leq \delta.\end{aligned}$$

Therefore, $\|\sigma_k\| = 1$ implies $|\,\|\tau_k\| - 1| \leq \delta$. Define

$$\gamma_k = \frac{\tau_k}{\|\tau_k\|}.$$

Then

$$\begin{aligned}\|\sigma_k - \gamma_k\| &\leq \|\sigma_k - \tau_k\| + \|\tau_k - \gamma_k\| \\ &\leq \delta + \left(1 - \frac{1}{\|\tau_k\|}\right)\|\tau_k\| = \delta + \|\tau_k\| - 1 \leq 2\delta < \varepsilon.\end{aligned}$$

Finally, $\gamma_k \in H$: Indeed, $\gamma_{x,k} \in V^x$ for all $x \in X$ implies

$$\gamma_k \in \sum_{i=1}^n f_i V^{x_i} = \sum_{i=1}^n f_i\langle \sigma_{i,1}, \ldots, \sigma_{i,n_i}\rangle \subset H. \qquad \square$$

Now the same perturbation argument as in [**13**, p. 198] shows

3.3. PROPOSITION. *Let E be a function module of AL-spaces and let $U \subset E$ be a finite dimensional subspace. Then for every positive $\varepsilon > 0$ there exists a finite dimensional subspace $V \subset E$ such that*

(i) $U \subset V$,

(ii) *There are finite dimensional AL-spaces $l_1(n_1), \ldots, l_m(n_m)$ such that the Banach-Mazur distance between V and the m-product $\prod_{i=1}^{m} l(n_i)$ is less than* $1 + \varepsilon$. □

The results of this section remain true if one changes from function modules of AL-spaces to function modules of $\mathscr{L}_p$-spaces for a fixed p, $1 \leq p \leq \infty$. For the case $p = \infty$ one gets as an interesting corollary:

Let E be a function module of Banach spaces over a compact base space and assume that every stalk E_x is a predual of an AL-space. Then E is a predual of an AL-space.

4. The Dunford-Pettis Property for function modules of AL-spaces. In this section we apply some results (and their proofs) of J. Bourgain [**2**] to function modules of AL-spaces. The proof of the next result is an immediate consequence of (3.3) and [**2**, Theorem 5]:

4.1. THEOREM. *Let E be a function module over a compact base space X and assume that all the stalks are AL-spaces. Then E and all duals of E have the Dunford-Pettis Property.* □

Of course, this result contains Bourgain's theorem that $C(X, L^1)$ is a Dunford-Pettis space as a special case. However, we used the key part of Bourgain's proof in our present result (namely Bourgain's Theorem 5).

4.2. COROLLARY. *Every injective Banach lattice has the Dunford-Pettis Property.*

Proof. Every injective Banach lattice may be represented as a function module of AL-spaces (see [**7**] or [**11**]). Hence (4.2) follows. □

4.3. COROLLARY. *Let E be a Banach lattice satisfying Cartwright's splitting property.*

(C) *For all $0 \leq a_1, a_2, b \in E$ and all real numbers r_1, r_2 such that $\|a_i\| \leq r_i$ and $\|a_1 + a_2 + b\| \leq r_1 + r_2$ there are $0 \leq b_1, b_2 \in E$ with $b_1 + b_2 = b$ and $\|a_i + b_i\| \leq r_i$, $i = 1, 2$.*

Then E and all its duals have the Dunford-Pettis Property.

Proof. Under the assumption (C), the second dual E'' of E is an injective Banach lattice (see [**3**]). Hence (4.3) follows from (4.2). □

Our last corollary deals with spaces of compact operators:

4.4. COROLLARY. *Let F be a predual of a L_1-space and let G be a G-space such that* 0 *is not an element of the weak $*$-closure of the unit ball of G'. Then the space of all compact operators $K(F, G)$ equipped with the operator norm has the Dunford-Pettis Property.*

Proof. By (2.1), we may assume that G is a function module over a compact space X such that all stalks are one-dimensional. Therefore, it follows from [**8**, 2.7] that $K(F, G)$ is isomorphic to a function module over the same space X with stalks F', i.e., $K(F, G)$ is isomorphic to a function module of AL-spaces. Hence (4.4) follows from (4.1). □

This last corollary leads to the conjecture that the space of all compact operators between two preducals of L_1-spaces is always a Dunford-Pettis space.

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