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SPACES OF S-COTYPE p $(0 \leqslant p \leqslant 2)$ AND p-STABLE MEASURES

BY

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Abstract. The aim of the paper is to give necessary and sufficient conditions for $\exp\{-\|Ta\|^p\}$ to be the characteristic functional of a Radon measure on E, where E is a Banach space with topological dual E', T-linear continuous operator from E' into L_p, and $0 \leqslant p \leqslant 2$.

I. Introduction. Let E be a real Banach space with dual E'. For a real number p $(0 < p \leqslant 2)$ X_p denotes a closed subspace of L_p. Let $T \in L(E', X_p)$, i.e. T is a linear continuous operator from E' into X_p. Consider the functional $f: E' \to R$ defined by

$$f(a) = \exp\{-\|Ta\|^p\}.$$

It is easy to see that $f(a)$ is the characteristic functional (ch. f.) of a cylindrical stable measure μ_T on E. The set of all operators $T \in L(E', X_p)$ such that μ_T can be extended into a Radon measure will be denoted by $\Lambda_p(E', X_p)$. $\Pi_p^{\text{dual}}(E', X_p)$ denotes the set of all operators $T \in L(E', X_p)$ such that $T^* \in \Pi_p(X_p', E)$, i.e. T^* is a p-summing operator from X_p' into E. In general, neither $\Lambda_p(E', X_p) \subset \Pi_p^{\text{dual}}(E', X_p)$ nor the converse inclusion hold. Our problem consists in characterizing those Banach E for which one of the following inclusion is valid for each space X_p:

(A) $$\Pi_p^{\text{dual}}(E', X_p) \subset \Lambda_p(E', X_p),$$

(B) $$\Lambda_p(E', X_p) \subset \Pi_p^{\text{dual}}(E', X_p).$$

For the case $p = 2$ the problems (A) and (B) have been solved by Chobanjan and Tarieladze [1]: (A) is always true for all Banach spaces E, (B) is true if and only if E is of cotype 2.

For the case $1 < p < 2$ the problem (A) has been solved by Linde, Mandrekar, Weron [5]: (A) is true if and only if E is of stable type p. Note that the authors of [5] also tried to solve the problem (B) but without complete success.

In this paper we shall try to solve the problem (B) for the case $0 < p \leqslant 2$. In Section 3 we introduce a definition of a space of S-cotype p $(0 < p \leqslant 2)$ and note that the notion of S-cotype 2 coincides with the notion of cotype 2. We shall show that the inclusion $\Lambda_p(E', X_p) \subset \Pi_p^{\text{dual}}(E'; X_p)$ holds for each space X_p if and only if E is of S-cotype p. We also extend a result of Garling [2] and Jain [3] on the structure of Gaussian measures on spaces of cotype 2 to the case of p-stable measures on spaces of S-cotype p $(1 < p \leqslant 2)$. It is interesting to note that the problem (A) is highly discontinuous in $p \in [1, 2]$ but the problem (B) is continuous in $p \in [1,2]$. Finally, in Section 4 we shall show some properties of spaces of S-cotype p.

2. Notation and definition. Let E be a real Banach space with dual E'. If μ is a Radon measure or, more generally, a cylindrical measure on E, then

$$\hat{\mu}(a) = \int_E \exp(i\langle x, a\rangle)\, d\mu(x), \qquad a \in E',$$

denotes the characteristic functional (ch.f.) of μ. A symmetric Radon measure μ is said to be *p-stable* $(0 < p \leqslant 2)$ if, for given $\alpha, \beta > 0$,

$$\hat{\mu}(\alpha a)\, \hat{\mu}(\beta a) = \hat{\mu}\big((\alpha^p + \beta^p)^{1/p} a\big) \quad \text{for all } a \in E'.$$

$R_p(E)$ denotes the set of all p-stable measures on E. Throughout this paper, X_p denotes a closed subspace of L_p $(0 < p \leqslant 2)$. If $T \in L(E', X_p)$, then functional $f(a)$ defined by

$$f(a) = \exp\{-\|Ta\|^p\}$$

is the characteristic functional (ch.f.) of a cylindrical stable measure μ_T on E. The set of all operators T such that μ_T extends to a Radon measure on E is denoted by $\Lambda_p(E', X_p)$. Of course, $\mu_T \in R_p(E)$ if $T \in \Lambda_p(E', X_p)$. Conversely, each measure $\mu \in R_p(E)$ can be written in this way. Let $\theta_1^{(p)}, \theta_2^{(p)}, \ldots$ be a sequence of independent identically distributed random variables with the ch.f. $\exp(-|t|^p)$. Then we say that E is of stable type p if for each sequence (x_n) in E with the property $\sum \|x_n\|^p < \infty$ the series $\sum x_n \theta_n^{(p)}$ converges a.s. A Banach space E is said to be of cotype 2 if for each sequence (x_n) in E such that the series $\sum x_n \theta_n^{(2)}$ converges a.s. in E it follows that $\sum \|x_n\|^2 < \infty$. If one replaces the sequence $(\theta_n^{(2)})$ by $(\theta_n^{(p)})$, then one obtains a definition of a space of a space of stable-cotype p. However, because of the tail behavior of $(\theta_n^{(p)})$, each Banach space is of stable-cotype p if $0 < p < 2$. A linear operator T from a Banach space E into a Banach F is p-summing if there exists a positive constant $C > 0$ such that

$$\big(\sum \|Tx_n\|^p\big)^{1/p} \leqslant C \sup_{\|a\| \leqslant 1} \big\{\sum |\langle x_n, a\rangle|^p\big\}^{1/p}$$

for any finite sequence $x_1, x_2, \ldots, x_n$ in E. Alternatively, if (x_n) is a sequence in E such that $\sum |\langle x_n, a\rangle|^p < \infty$ for each a in E', then $\sum \|Tx_n\|^p < \infty$. The class of all p-summing from E into F is denoted by $\Pi_p(E, F)$. If $0 < p < q$, then $\Pi_p(E, F) \subset \Pi_p(E, F)$. For more information about p-summing operators we refer the readers to [10].

3. Spaces of S-cotype p $(0 \leqslant p \leqslant 2)$ and p-stable measures.

3.1. Definition. A Banach space E is said to be of *S-cotype p* $(0 < p \leqslant 2)$ if, for each sequence (x_n) in E, such that

$$1-\exp\{-\sum |\langle x_n, a\rangle|^p\} \leqslant 1-\hat{\mu}(a)$$

for all $a \in E'$ and some $\mu \in R_p(E)$, we have $\sum \|x_n\|^p < \infty$.

3.2. Proposition. *The following are equivalent*:

(1) *E is of S-cotype 2.*

(2) *E is of cotype 2.*

Proof. (1)$\Rightarrow$(2) Let (x_n) be a sequence in E such that the series $\sum x_n \theta_n^{(2)}$ converges a.s. We have to show that $\sum \|x_n\|^2 < \infty$. Let μ be the distribution of $\sum x_n \theta_n^{(2)}$. Then $\mu \in R_2(E)$ and

$$\hat{\mu}(a) = \exp\{-\sum |\langle x_n, a\rangle|^2\}.$$

From definition 3.1. it follows that $\sum \|x_n\|^2 < \infty$.

(2)$\Rightarrow$(1) Let (x_n) be a sequence in E such that

$$1-\exp\{-\sum |\langle x_n, a\rangle|^2\} \leqslant 1-\hat{\mu}(a)$$

for all $a \in E'$ and some $\mu \in R_2(E)$. Let ν be a Gaussian cylindrical measure with the covariance function R_ν defined by

$$R_\nu(a, a) = \sum |\langle x_n, a\rangle|^2. \tag{3.1}$$

From (3.1) we have $R_\nu(a, a) \leqslant \langle R_\mu a, a\rangle$, where R_μ is the covariance operator of the Gaussian measure μ. By a known result in [14] we conclude that ν is in fact a Radon Gaussian measure. From this it follows that the series $\sum x_n \theta_n^{(2)}$ converges a.s. Since E is of cotype 2, we have $\sum \|x_n\|^2 < \infty$.

Now we investigate operators T from E' into a closed subspace X_p of L_p $(1 \leqslant p \leqslant 2)$ for which $\exp\{-\|Ta\|^p\}$ is the ch.f. of a Radon measure on E. The set of all those operators is denoted by $\Lambda_p(E', X_p)$.

3.3. Theorem. *Let $1 \leqslant p \leqslant 2$. Then the following are equivalent*:

(1) *E is of S-cotype p.*

(2) *For each space X_p we have*

$$\Lambda_p(E', X_p) \subset \Pi_p^{\text{dual}}(E', X_p).$$

Proof. (1)$\Rightarrow$(2). Let $T \in \Lambda_p(E', X_p)$ and let (g_n) be a sequence in X'_p such that $\sum |\langle g_n, x\rangle|^p < \infty$ for each $x \in X_p$. We have to show that $\sum \|T^* g_n\|^p < \infty$.

Consider the operator $S\colon X_p \to l_p$ defined by $Sx = (\langle g_n, x\rangle)_{n=1}^{\infty}$. Evidently, S is a linear continuous operator and we have $S^* e_n = g_n$, where (e_n) is the sequence of unit vectors in l_q $(p^{-1}+q^{-1} = 1)$. We have

$$\|STa\|^p \leqslant \|S\|^p \|Ta\|^p. \tag{3.2}$$

On the other hand

$$\|STa\|^p = \sum |\langle STa, e_n\rangle|^p = \sum |\langle T^* S^* e_n, a\rangle|^p. \tag{3.3}$$

From (3.2) and (3.3) we have

$$1-\exp\{-\sum |\langle T^* S^* e_n, a\rangle|^p\} \leqslant 1-\hat{\mu}(a), \tag{3.4}$$

where μ is the p-stable measure with the ch.f.

$$\hat{\mu}(a) = \exp\{-\|S\|^p \|Ta\|^p\}.$$

By assumption that E is of S-cotype p, from (3.4) it follows that

$$\sum \|T^* S^* e_n\|^p = \sum \|T^* g_n\|^p < \infty.$$

(2)$\Rightarrow$(1). Assume that E is not of S-cotype p. Then there exist $\mu \in R_p(E)$ and a sequence (x_n) in E satisfying

$$1-\exp\{-\sum |\langle x_n, a\rangle|^p\} \leqslant 1-\hat{\mu}(a) \text{ for all } a \in E', \tag{3.5}$$

but $\sum \|x_n\|^p = \infty$.

Suppose that $\hat{\mu}(a) = \exp\{-\|Ta\|^p\}$ where T is a linear continuous operator from E' into L_p. Put $X_p = \overline{TE'}$; we have $T \in \Lambda_p(E', X_p)$. Now we shall show that $T \notin \Pi_p^{\text{dual}}(E', X_p)$ i.e. T^* is not p-summing. Define a linear operator $B\colon E' \to l_p$ by $Ba = (\langle x_n, a\rangle)_{n=1}^{\infty}$. We shall now construct a linear continuous operator $V\colon X_p \to l_p$ such that $B = V_0 T$.

At first, we define an operator $V\colon T(E') \to l_p$ by $V(Ta) = Ba$.

V is well defined. Indeed, by inequality (3.5) we have

$$\|B(a_1-a_2)\| \leqslant \|T(a_1-a_2)\|, \quad a_1, a_2 \in E'.$$

Hence, $Ta_1 = Ta_2$ implies $Ba_1 = Ba_2$.

Evidently, V is linear and continuous. Since $T(E')$ is dense in X_p, V admits the unique extension to X_p and we have $B = V_0 T$.

Suppose in contrary that $T^* \in \Pi_p(X_p', E)$. Then $B^* = T^* V^* \in \Pi_p(l_q, E)$. Therefore $\sum \|B^* e_n\|^p = \sum \|x_n\|^p < \infty$. A contradiction. Thus we have T^* is not p-summing as desired.

Remark. The above proof has some resemblance to the proof of Theorem 3.5 in [13].

Theorem 3.3 and Theorem 2 in [5] allow us to characterize spaces E where $T \in \Lambda_p(E', X_p)$ if and only if $T^* \in \Pi_p(X_p', E)$. In the case $p = 2$ these are exactly spaces E of cotype 2 [1].

3.4. COROLLARY. *Let $1 \leqslant p < 2$. Then the following are equivalent:*

(1) *E is of stable type p and S-cotype p.*

(2) *For each space X_p, $\Lambda_p(E', X_p) = \Pi_p^{\text{dual}}(E', X_p)$.*

Remark. (1) is equivalent to:

(1′) E imbeds in L_q $(p < q \leqslant 2)$ (see Corollary 4.8 below).

Next, we shall prove the following Theorem which gives information on the structure of p-stable measures on spaces of S-cotype p.

3.5. THEOREM. (1) *Suppose that E is of S-cotype p, in addition X_p is of stable type p $(1 < p \leqslant 2)$. Then each p-stable measure μ_T where $T \in \Lambda_p(E', X_p)$ is a continuous image of a p-stable measure ν on some closed subspace of L_p.*

(2) *If each p-stable measure μ on a Banach space E is a continuous image of a p-stable measure ν on some closed subspace of L_p, then E must be of S-cotype p.*

Proof. (1) Let $\mu = \mu_T$ where $T \in \Lambda_p(E', X_p)$. Because E is of S-cotype p, by Theorem 3.3 $T^* \in \Pi_p(X'_p, E)$. By the factorization theorem [10]

$$T^*\colon X'_p \xrightarrow{U} S \xrightarrow{V} E,$$

where S is a closed subspace of L_p, $V \in L(S, E)$ and $U \in \Pi_p(X'_p, S)$. Let γ_p be the canonical cylindrical measure on X'_p with the ch.f. $\exp\{-\|x\|_{X_p}^p\}$. We have $\mu_T = T^*(\gamma_p) = V[U(\gamma_p)]$. Since X_p is of stable type p by Maurey-Pisier's Theorem [6] the operator U which is p-summing is also r-summing for $1 < r < p$. Because γ_p is a cylindrical measure of type r for $r < p$ then in view of Schwartz's Theorem [12] $\nu = U(\gamma_p)$ is a Radon measure on S. Evidently, ν is p-stable and we have $\mu_T = V(\nu)$.

(2) Using the above Theorem 3.3 we shall show that $\Lambda_p(E', X_p) \subset \Pi_p^{\text{dual}}(E', X_p)$ for each space X_p. Let $T \in \Lambda_p(E', X_p)$. By hypothesis, there exist a closed subspace S of L_p, a p-stable measure ν on S and a continuous linear $V\colon S \to E$ such that $\mu_T = V(\nu)$. We may clearly suppose that V is 1-1 and thus $V^*(E')$ is dense in S'. Suppose that $\hat{\nu}(s') = \exp\{-\|T_\nu s'\|^p\}$ for $s' \in S'$. Then

$$\hat{\mu}_T(a) = \exp\{-\|Ta\|^p\} = \exp\{-\|T_\nu V^* a\|^p\}. \tag{3.6}$$

We shall now construct a linear continuous operator $W\colon S' \to X_p$ such that $T = W_0 V^*$. At first, we define an operator $W\colon V^*(E') \to X_p$ by $W(V^* a) = Ta$. W is well defined. Indeed, by equality (3.6) we have

$$\|T(a_1 - a_2)\| = \|T_\nu(V^* a_1 - V^* a_2)\|, \quad a_1, a_2 \in E'.$$

Then $V^* a_1 = V^* a_2$ implies $Ta_1 = Ta_2$.

Evidently, W is linear and continuous. Since $V^*(E')$ is dense in S', W admits a unique extension to S and we have $T = W V^*$. It is easily seen that

$$\hat{\nu}(s') = \exp\{-\|T_\nu s'\|^p\} = \exp\{-\|Ws'\|^p\}.$$

Thus $W \in \Lambda_p(S', X_p)$. Since S is of S-cotype p (see Corollary 4.3 below), $W^* \in \Pi_p(X'_p, S)$ by Theorem 3.3. Consequently, $T^* = VW^*$ is p-summing and the proof is finished.

3.6 COROLLARY [2]. *E is of cotype 2 if and only if each Gaussian measure on E is a continuous image of some Gaussian measure on the Hilbert space H.*

4. Some properties of spaces of S-cotype p.

4.1 THEOREM. *If a Banach space E is of S-cotype p, then it is also of S-cotype q for $0 < p \leqslant q$.*

Proof. Applying Theorem 3.1 we shall show that $\Lambda_q(E', X_q) \subset \Pi_q^{\mathrm{dual}}(E', X_q)$ for each space X_q. Let $T \in \Lambda_q(E', X_q)$. Then $\exp\{-\|Ta\|^q\}$ is ch.f. of a Radon measure on E. By Theorem 2 [8] $f(a) = \exp\{-\|Ta\|^p\}$ is also the ch.f. of a Radon measure on E. Thus $T \in \Lambda_p(E', X_q)$ (since $L_q \leftrightarrow L_p$ if $p \leqslant q \leqslant 2$, X_q is considered as a closed subspace of L_p). Since E is of S-cotype p by Theorem 3.3 T^* is p-summing. Because of the inclusion property of the ideals of p-summing operators [10] T^* is also q-summing.

4.2. THEOREM. *If E is an (S)-space, then it is of S-cotype p for $0 < p \leqslant 2$.*

Recall that E is an (S)-space if there exists a topology τ on E' such that a functional $f\colon E' \to C$ is positive definitive, τ-continuous with $f(0) = 1$ if and only if f is the ch.f. of a probability measure μ on E. The topology τ is called *S-topology*. It is known that (see [9], [7]) a Banach space E with the approximation property is an S-space if and only if E can imbed in some L_0. Each closed subspace of L_p $(1 \leqslant p \leqslant 2)$ is an (S)-space. For more information about (S)-spaces we refer the reader to [9], [7].

Proof of Theorem 4.2. In view of Theorem 4.1 it remains for us to prove for $0 < p < 2$. Let (x_n) be a sequence in E such that

$$1 - \exp\{-\sum |\langle x_n, a\rangle|^p\} \leqslant 1 - \hat{\mu}(a) \tag{4.1}$$

for all $a \in E'$ and some $\mu \in R_p(E)$.

Let ν be the stable cylindrical measure with ch.f.

$$\hat{\nu}(a) = \exp\{-\sum |\langle x_n, a\rangle|^p\}.$$

Since μ is a Radon measure, $\hat{\mu}(a)$ is τ-continuous where τ is S-topology on E'. From (4.1) it follows that $\hat{\nu}(a)$ is τ-continuous and thus it is the ch.f. of a Radon measure on E. Then by Ito-Nisio's Theorem we conclude that the series $\sum x_n \theta_n^{(p)}$ converges a.s. Since $p < 2$, we have $\sum \|x_n\|^p < \infty$.

4.3. COROLLARY. *Each closed subspace of L_p $(1 \leqslant p \leqslant 2)$ is of S-cotype p for $0 < p \leqslant 2$.*

Theorem 4.1 and Theorem 4.2 lead us to introduce the following

4.4. Definition. An (S)-space is said to be of S-cotype 0.

4.5 THEOREM. *If a Banach space is of stable type p and of S-cotype p $(0 < p \leqslant 2)$ then it imbeds in L_p.*

Proof. According to the Lindenstrauss-Pełczynski's criterion of imbedding a Banach in L_p [11] we shall show that if (x_n) and (y_n) are two sequences in E such that

$$(4.2) \qquad \sum |\langle x_n, a\rangle|^p \leqslant \sum |\langle y_n, a\rangle|^p \quad \text{for all } a \in E' \text{ and } \sum \|y_n\|^p < \infty,$$

then $\sum \|x_n\|^p < \infty$.

Indeed, let (x_n) and (y_n) be two sequences in E satisfying (4.2). Since E is of stable type p we find that the series $\sum y_n \theta_n^{(p)}$ converges a.s. Let μ be the distribution of $\sum y_n \theta_n^{(p)}$. Then $\mu \in R_p(E)$ and $\hat{\mu}(a) = \exp\{-\sum |\langle y_n, a\rangle|^p\}$. From (4.2) we have

$$1 - \exp\{-\sum |\langle x_n, a\rangle|^p\} \leqslant 1 - \hat{\mu}(a).$$

By the assumption that E is of S-cotype p we have $\sum \|x_n\|^p < \infty$.

4.6. COROLLARY. *A Banach space of S-cotype $p < 1$ can imbed in L_p.*

Indeed, since every Banach space is of stable type p if $0 < p < 1$ [6]. In the case $p = 0$ this is a known result about (S)-spaces (see [9]).

4.7. COROLLARY. *If a Banach space with the approximation property is of S-cotype $p < 1$ then it is of S-cotype* 0.

The following proposition gives the description of those spaces which are of stable type p and S-cotype p for $1 \leqslant p \leqslant 2$.

4.8. PROPOSITION. *Let $1 \leqslant p \leqslant 2$. Then the following are equivalent:*

(1) *E is of stable type p and S-cotype p.*

(2) *E imbeds in L_q where $q = 2$ if $p = 2$, $p < q < 2$ if $p < 2$.*

In the case $p = 1$ (1) is equivalent to

(1′) *E is isomorphic to a reflexive subspace of L_1* (see [11]).

Proof. The inclusion (1)→(2) follows from Theorem 4.5 and a Rosenthal's Theorem [11] which states that a closed subspace of L_p is of stable type p $(1 \leqslant p < 2)$ if and only if it imbeds in $L_q (p < q)$. The inclusion (2)→(1) follows from Corollary 4.3 and the fact that L_q $(p < q)$ is of stable type p.

4.9. PROPOSITION. *Each Banach space of M-cotype p in the sense of Mouchtari is of S-cotype p.*

The notion of M-cotype p was introduced by Mouchtari in [8]. Let σ_p denote the coarest topology on E' for which all the ch.f. of p-stable measures are continuous. A Banach space E is said to be of M-cotype p $(0 < p \leqslant 2)$ if for a cylindrical measure ν on E to be extended into a Radon measure it suffices that the ch.f. $\hat{\nu}(a)$ is σ_p-continuous.

Proof. In the case $p = 2$ the notion of M-cotype 2 is identical with the notion of cotype 2 [8] and thus it is identical with the notion of S-cotype 2 by Proposition 3.2. It remains to prove the case $0 < p < 2$. Let (x_n) be a sequence in E such that

$$(4.3) \qquad 1-\exp\{-\sum|\langle x_n, a\rangle|^p\} \leqslant 1-\hat{\mu}(a)$$

for all $a \in E'$ and some $\mu \in R_p(E)$.

Let ν be the cylindrical measure with the ch.f.

$$\hat{\nu}(a) = \exp\{-\sum|\langle x_n, a\rangle|^p\}.$$

From (4.3) it follows that $\hat{\nu}(a)$ is σ_p-continuous. By the assumption that E is of M-cotype p, $\hat{\nu}(a)$ is a ch.f. of a Radon measure on E. From Ito-Nisio's Theorem it follows that the series $\sum x_n \theta_n^{(p)}$ converges a.s. Since $p < 2$ we have $\sum \|x_n\|^p < \infty$.

4.10. Proposition. *If $p < q$, $q > 1$, then there exist spaces of S-cotype q which are not of S-cotype p.*

Proof. Consider the space $l_s\,(l_t)$, where $q > s > t > p$, $t > 1$. By Theorem 7 in [8] $l_s\,(l_t)$ is of M-cotype q hence it is of S-cotype q in view of Proposition 4.9. Assume that $l_s\,(l_t)$ is of S-cotype p. By Proposition 8 in [8] $l_s\,(l_t)$ is of stable type p. Therefore, by Theorem 4.5, $l_s\,(l_t)$ imbeds in L_p. But this contradicts the Proposition 9 in [8].

Problem. Are spaces of S-cotype p exactly spaces of M-cotype p $(0 < p < 2)$?

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