WEAK FACTORIZATION AND HANKEL FORMS FOR WEIGHTED BERGMAN SPACES ON THE UNIT BALL

JORDI PAU AND RUHAN ZHAO

ABSTRACT. We establish weak factorizations for a weighted Bergman space $A^p_\alpha$, with $1 < p < \infty$, into two weighted Bergman spaces on the unit ball of $\mathbb{C}^n$. To obtain this result, we characterize bounded Hankel forms on weighted Bergman spaces on the unit ball of $\mathbb{C}^n$.

1. INTRODUCTION

A classical theorem of Riesz asserts that any function in the Hardy space $H^p$ on the unit disk can be factored as $f = Bg$ with $\|f\|_{H^p} = \|g\|_{H^p}$, where $B$ is a Blaschke product and $g$ is an $H^p$-function with no zeros on the unit disk. An immediate consequence of that result is that any function in the Hardy space $H^p$ admits a “strong” factorization $f = f_1f_2$ with $f_1 \in H^{p_1}$, $f_2 \in H^{p_2}$ and $\|f\|_{H^p} \cdot \|f\|_{H^p} = \|f\|_{H^p}$, for any $p_1$ and $p_2$ determined by the condition $1/p = 1/p_1 + 1/p_2$. In [12], C. Horowitz obtained strong factorizations of functions in a weighted Bergman space on the unit disk into functions of two weighted Bergman spaces with the same weight. These strong factorization results are no longer possible to obtain [11] in the setting of Hardy and Bergman spaces in the unit ball of the complex euclidian space $\mathbb{C}^n$ of dimension $n$ when $n \geq 2$, but it is still possible to obtain some “weak” factorizations for functions in these spaces.

For two Banach spaces (or $F$-spaces) of functions, $A$ and $B$, defined on the same domain, the weakly factored space $A \odot B$ is defined as the completion of finite sums

$$f = \sum_k \varphi_k \psi_k, \quad \{\varphi_k\} \subset A, \{\psi_k\} \subset B,$$

with the following norm:

$$\|f\|_{A \odot B} = \inf \left\{ \sum_k \|\varphi_k\|_A \|\psi_k\|_B : f = \sum_k \varphi_k \psi_k \right\}.$$

When $0 < p \leq 1$, weak factorizations for the Hardy spaces $H^p$ and the weighted Bergman spaces $A^p_\alpha$ on the unit ball of $\mathbb{C}^n$ are well known (see [6] and [9] for Hardy spaces; and [5], [20] or [25, Corollary 2.33] for Bergman spaces). However, when $1 < p < \infty$, even for unweighted Bergman spaces the problem is still open (see, for example [4]).

In this paper we completely solve the above problem for Bergman spaces by establishing weak factorizations for a weighted Bergman space $A^q_\beta$, with $1 < q < \infty$ and $\beta > -1$, into
two weighted Bergman spaces with non necessarily the same weight, on the unit ball \( \mathbb{B}_n \) of \( \mathbb{C}^n \). The following is our main result.

**Theorem 1.** Let \( 0 < q < \infty \) and \( \beta > -1 \). Then

\[
A^q_\beta(\mathbb{B}_n) = A^{p_1}_{\alpha_1}(\mathbb{B}_n) \circ A^{p_2}_{\alpha_2}(\mathbb{B}_n)
\]

for any \( p_1, p_2 > 0 \) and \( \alpha_1, \alpha_2 > -1 \) satisfying

\[
\frac{1}{p_1} + \frac{1}{p_2} = \frac{1}{q}, \quad \frac{\alpha_1}{p_1} + \frac{\alpha_2}{p_2} = \frac{\beta}{q}.
\]

In this context, by “\( = \)” we mean equality of the function spaces and equivalence of the norms. We mention here that the case \( 0 < q \leq 1 \) is well known, and follows easily from the atomic decomposition for Bergman spaces. Our contribution here is the case \( q > 1 \).

Now we are going to recall the definition of the weighted Bergman spaces. First we use

\[
\langle z, w \rangle = z_1 \bar{w}_1 + \cdots + z_n \bar{w}_n
\]

to denote the inner product of \( z \) and \( w \), and

\[
|z| = \sqrt{\langle z, z \rangle} = \sqrt{|z_1|^2 + \cdots + |z_n|^2}
\]

to denote the norm of \( z \) in \( \mathbb{C}^n \). Let \( \mathbb{B}_n = \{ z \in \mathbb{C}^n : |z| < 1 \} \) be the unit ball in \( \mathbb{C}^n \) and \( \mathbb{S}_n = \{ z \in \mathbb{C}^n : |z| = 1 \} \) be the unit sphere in \( \mathbb{C}^n \). Let \( H(\mathbb{B}_n) \) be the space of all analytic functions on \( \mathbb{B}_n \). We use \( dv \) to denote the normalized volume measure on \( \mathbb{B}_n \) and \( d\sigma \) to denote the normalized area measure on \( \mathbb{S}_n \). For \( -1 < \alpha < \infty \), we let \( dv_\alpha(z) = c_\alpha(1 - |z|^2)\alpha \ dv(z) \) denote the normalized weighted volume measure on \( \mathbb{B}_n \), where \( c_\alpha = \Gamma(n + \alpha + 1)/[\pi \Gamma(\alpha + 1)] \).

For \( 0 < p < \infty \) and \( -1 < \alpha < \infty \), let \( L^p(\mathbb{B}_n, dv_\alpha) \) be the weighted Lebesgue space which contains measurable functions \( f \) on \( \mathbb{B}_n \) such that

\[
\|f\|_{p,\alpha} = \int_{\mathbb{B}_n} |f(z)|^p \ dv_\alpha(z) < \infty.
\]

Denote by \( A^p_\alpha = L^p(\mathbb{B}_n, dv_\alpha) \cap H(\mathbb{B}_n) \), the weighted Bergman space on \( \mathbb{B}_n \), with the same norm as above. If \( \alpha = 0 \), we simply write them as \( L^p(\mathbb{B}_n, dv) \) and \( A^p \) respectively and \( \|f\|_p \) for the norm of \( f \) in these spaces.

It is a well-known fact that to obtain weak factorization results is equivalent to give a “good” description of the boundedness of certain Hankel forms. A Hankel form is a bilinear form \( B \) on a space of analytic functions such that for any \( f \) and \( g \), \( B(f, g) \) is a linear function of \( f \). These forms have been extensively studied on Hardy spaces and on Bergman spaces. For the case of the Hardy space on the unit disk, a classical result by Nehari [13] says that the Hankel form

\[
B_b(f, g) := \langle fg, b \rangle
\]

(under the usual integral pair for Hardy spaces) with an analytic symbol \( b \) is bounded on \( H^2 \times H^2 \) if and only if \( b \in BMOA \), the space of analytic functions of bounded mean oscillation. The proof used the fact that a function in \( H^1 \) can be factored into product of two functions in \( H^2 \). Unfortunately, such strong factorization is not possible (see [11]) for Hardy spaces in the unit ball \( \mathbb{B}_n \) of \( \mathbb{C}^n \). However, Coifman, Rochberg and Weiss [8] were able to generalize Nehari’s result to the unit ball \( \mathbb{B}_n \) by using a weak factorization of \( H^1 \). Namely, they proved that

\[
H^2(\mathbb{B}_n) \circ H^2(\mathbb{B}_n) = H^1(\mathbb{B}_n).
\]
Our approach to the problem for weighted Bergman spaces on the unit ball is the opposite to the one of Coifman, Rochberg and Weiss in \cite{coifman}. We first characterize boundedness of the Hankel forms on weighted Bergman spaces, and with this result the weak factorization easily follows.

Given $\alpha > -1$ and a holomorphic symbol function $b$ we define the associated Hankel type bilinear form $T^\alpha_b$ for polynomials $f$ and $g$ by

$$T^\alpha_b(f, g) = \langle f, b \rangle_\alpha,$$

where the integral pair $\langle \cdot, \cdot \rangle_\alpha$ is defined as

$$\langle \varphi, \psi \rangle_\alpha = \int_{\mathbb{B}_n} \varphi(z) \overline{\psi(z)} \, dv_\alpha(z).$$

Since the polynomials are dense in the weighted Bergman spaces, the Hankel form $T^\alpha_b$ is densely defined on $A^\alpha_{p_1} \times A^\alpha_{p_2}$ for any $p_1, p_2 > 0$ and any $\alpha_1, \alpha_2 > -1$. We say that $T^\alpha_b$ is bounded on $A^\alpha_{p_1} \times A^\alpha_{p_2}$ if there exists a positive constant $C$ such that

$$|T^\alpha_b(f, g)| \leq C\|f\|_{p_1, \alpha_1}\|g\|_{p_2, \alpha_2}.$$

The norm of $T^\alpha_b$ is given by

$$\|T^\alpha_b\| = \|T^\alpha_b\|_{A^\alpha_{p_1} \times A^\alpha_{p_2}} := \sup\{|T^\alpha_b(f, g)| : \|f\|_{p_1, \alpha_1} = \|g\|_{p_2, \alpha_2} = 1\}.$$

The next result characterizes boundedness of the Hankel form $T^\alpha_b$ acting on $A^\alpha_{p_1} \times A^\alpha_{p_2}$. We will see in Section 3 that this implies the weak factorization in Theorem 1.

**Theorem 2.** Let $1 < p_1, p_2 < \infty$, and $\alpha, \alpha_1, \alpha_2 > -1$ satisfy

$$\frac{1}{p_1} + \frac{1}{p_2} < 1, \quad \frac{1 + \alpha_1}{p_1} + \frac{1 + \alpha_2}{p_2} < 1 + \alpha.$$

Then $T^\alpha_b$ is bounded on $A^\alpha_{p_1} \times A^\alpha_{p_2}$ if and only if $b \in A^q_{\beta'}$, where $q$ and $\beta'$ are real numbers satisfying (1), and $q'$ and $\beta'$ are determined by the condition

$$\frac{1}{q} + \frac{1}{q'} = 1, \quad \frac{\beta}{q} + \frac{\beta'}{q'} = \alpha.$$

Furthermore, we have $\|T^\alpha_b\| \approx \|b\|_{q', \beta'}$.

**Remarks.** Note that, condition (3) guarantees that $q' > 1$ and $\beta' > -1$. When $q$ and $\beta$ satisfy condition (1), automatically we would have $\beta > -1$ (to see this, simply add two equations in (1) together). By a general duality theorem for weighted Bergman spaces (see Theorem A in Section 2), the condition $b \in A^q_{\beta'}$ means that the symbol $b$ belongs to the dual space of $A^q_{\beta'}$ under the pairing given by (2).

It turns out that boundedness of the Hankel form $T^\alpha_b$ is equivalent to boundedness of a (small) Hankel operator, which we are going to introduce in a moment. Let $\alpha > -1$. It is well-known that, the integral operator

$$P_\alpha f(z) = \int_{\mathbb{B}_n} \frac{f(w)}{(1 - \langle z, w \rangle)^{n+1+\alpha}} \, dv_\alpha(w)$$

is the orthogonal projection from $L^2(\mathbb{B}_n, dv_\alpha)$ onto the weighted Bergman space $A^2_\alpha$. The above formula can be used to extend $P_\alpha$ to a linear operator from $L^1(\mathbb{B}_n, dv_\alpha)$ into $H(\mathbb{B}_n)$. For $1 < p < \infty$, $P_\alpha$ is a bounded operator from $L^p(\mathbb{B}_n, dv_\alpha)$ onto $A^p_\alpha$.

Denote by $A^p_\alpha$ the conjugate analytic functions $f$ on $\mathbb{B}_n$ that are in $L^p(\mathbb{B}_n, dv_\alpha)$. Clearly, $A^p_\alpha = \{f^\cdot : f \in A^p_\alpha\}$. 

\[ \overline{A^p_\alpha} = \{ f^\cdot : f \in A^p_\alpha \} . \]
Let $Q_\alpha$ denote the orthogonal projection from $L^2(\mathbb{B}_n, dv_\alpha)$ onto $A^2_\alpha$. Clearly one has
\[
Q_\alpha f(z) = P_\alpha f(z) = \int_{\mathbb{B}_n} \frac{f(w)}{(1 - \langle w, z \rangle)^{n+1+\alpha}} dv_\alpha(w).
\]
Given $f \in L^1(\mathbb{B}_n, dv_\alpha)$ and a polynomial $g$, the weighted (small) Hankel operator is defined by
\[
h_\alpha^f g = Q_\alpha(fg).
\]
Due to the density of polynomials, the small Hankel operator $h_\alpha^f$ is densely defined on the weighted Bergman space $A^2_\alpha$ for $1 \leq p < \infty$. We will study boundedness of the small Hankel operator with conjugate analytic symbols, that is, $h_\alpha^f$ where $f \in H(\mathbb{B}_n)$, from $A^p_{\alpha_1}$ to $A^p_{\alpha_2}$ with $0 < p_2 < p_1 < \infty$.

**Theorem 3.** Let $1 < p_2 < p_1 < \infty$ and $\alpha_1, \alpha_2 > -1$ such that
\[
\frac{1 + \alpha_1}{p_1} < \frac{1 + \alpha_2}{p_2}.
\]
Let $f \in H(\mathbb{B}_n)$ and $\alpha$ such that
\[
1 + \alpha > \frac{1 + \alpha_2}{p_2}.
\]
Then $h_\alpha^f : A^p_{\alpha_1} \to A^p_{\alpha_2}$ is bounded if and only if $f \in A^q_{\beta}$, where $q$ and $\beta$ are real numbers such that
\[
\frac{1}{q} = \frac{1}{p_2} - \frac{1}{p_1}, \quad \frac{\beta}{q} = \frac{\alpha_2}{p_2} - \frac{\alpha_1}{p_1}.
\]
Moreover, we have $\|h_\alpha^f\| \leq \|f\|_{q, \beta}$.

**Remarks.** Condition (5) guarantees that $\beta > -1$. It is known that, when $0 < p_2 < p_1 < \infty$, $A^p_{\alpha_1} \subset A^p_{\alpha_2}$ if and only if (5) is true (see [23, Theorem 70]). Hence the above result concerns the boundedness of $h_\alpha^f$ from a smaller space to a larger space. Also, by [25, Theorem 2.11], condition (6) means that the integral operator $P_\alpha$ is a bounded projection from $L^p(\mathbb{B}_n, dv_\alpha)$ onto $A^p_{\alpha_2}$.

If one considers the operator
\[
S_\alpha^f g = h_\alpha^f g(z) = P_\alpha (fg),
\]
clearly, the boundedness of $h_\alpha^f$ is equivalent to the boundedness of $S_\alpha^f$ from $A^p_{\alpha_1}$ to $A^p_{\alpha_2}$, and the norms of $h_\alpha^f$ and $S_\alpha^f$ are equivalent. Now, if $g \in A^p_{\alpha_1}$ and $h \in A^p_{\alpha_2}$, by Fubini’s theorem we easily obtain
\[
T_\alpha f(g, h) = (gh, f)_\alpha = (h, P_\alpha(fg))_\alpha = (h, S_\alpha^f g)_\alpha.
\]
Hence, for $p_2 > 1$, by duality (see Theorem 1 in Section 2), the Hankel form $T_\alpha^p$ is bounded on $A^p_{\alpha_1} \times A^p_{\alpha_2}$ if and only if the small Hankel operator $h_\alpha^f$ is bounded from $A^p_{\alpha_1}$ to $A^p_{\alpha_2}$, with equivalent norms. Here, the numbers $\alpha'$ and $p'$ are defined by the relation
\[
\frac{1}{p'} + \frac{1}{p} = 1, \quad \alpha = \frac{\alpha_2}{p} + \frac{\alpha'}{p'}. \quad \alpha' = \frac{\alpha_1}{p} + \frac{\alpha_2}{p_2}.
\]
Comparing Theorem 2 with Theorem 3, notice that the first inequality in (5) is equivalent to condition $1 < p_2 < p_1 < \infty$. Also, when $p_2$ and $\alpha_2$ are replaced by $p'_2$ and $\alpha'_2$, condition (6) turns out to be equivalent to $\alpha_2 > -1$, and therefore is always satisfied; and
the second inequality in (3) is equivalent to condition (5). Therefore, Theorem 3 implies Theorem 2.

The paper is organized as follows: in Section 2 we give some necessary concepts and recall some key results which are needed in our proof of the main result. In Section 3 we give in detail the connection between weak factorizations and Hankel forms. The proof of Theorem 3 is given in Section 4.

In the following, the notation $A \lesssim B$ means that there is a positive constant $C$ such that $A \leq CB$, and the notation $A \sim B$ means that both $A \lesssim B$ and $B \lesssim A$ hold.

2. Preliminaries

We need the following duality theorem. In this generality the result is due to Luecking [16] (see also, Theorem 2.12 in [25]).

**Theorem A.** Suppose $\beta, \beta' > -1$ and $1 < q < \infty$. Then

$$(A_\beta^q)^* = A_{\beta'}^{q'},$$

(with equivalent norms) under the integral pair $\langle \cdot, \cdot \rangle_\alpha$ given by (2), where

$$\frac{1}{q} + \frac{1}{q'} = 1, \quad \alpha = \frac{\beta}{q} + \frac{\beta'}{q'}.$$  

We need the following well known integral estimate that can be found, for example, in [25, Theorem 1.12].

**Lemma B.** Let $t > -1$ and $s > 0$. There is a positive constant $C$ such that

$$\int_{B_n} \frac{(1 - |w|^2)^t}{|1 - \langle z, w \rangle|^{n+1+s}} dv(w) \leq C (1 - |z|^2)^{-s}$$

for all $z \in B_n$.

For any $a \in B_n$ with $a \neq 0$, we denote by $\varphi_a(z)$ the M"obius transformation on $B_n$ that exchanges 0 and $a$. It is known that, for any $z \in B_n$

$$\varphi_a(z) = \frac{a - P_a(z) - s_a Q_a(z)}{1 - \langle z, a \rangle},$$

where $s_a = 1 - |a|^2$, $P_a$ is the orthogonal projection from $\mathbb{C}^n$ onto the one dimensional subspace $[a]$ generated by $a$, and $Q_a$ is the orthogonal projection from $\mathbb{C}^n$ onto the orthogonal complement of $[a]$. When $a = 0$, $\varphi_a(z) = -z$. $\varphi_a$ has the following properties: $\varphi_a \circ \varphi_a(z) = z$, and

$$1 - |\varphi_a(z)|^2 = \frac{(1 - |a|^2)(1 - |z|^2)}{|1 - \langle z, a \rangle|^2}.$$  

For $z, w \in B_n$, the pseudo-hyperbolic distance between $z$ and $w$ is defined by

$$\rho(z, w) = |\varphi_z(w)|,$$

and the hyperbolic distance on $B_n$ between $z$ and $w$ induced by the Bergman metric is given by

$$\beta(z, w) = \tanh \rho(z, w).$$

For $z \in B_n$ and $r > 0$, the Bergman metric ball at $z$ is given by

$$D(z, r) = \{ w \in B_n : \beta(z, w) < r \}.$$
It is known that, for a fixed \( r > 0 \), the weighted volume
\[
v_\alpha(D(z, r)) \propto (1 - |z|^2)^{n+1+\alpha}.
\]
We refer to [25] for all of the above facts.

A sequence \( \{a_k\} \) of points in \( \mathbb{B}_n \) is a separated sequence (in Bergman metric) if there exists a positive constant \( \delta > 0 \) such that \( \beta(z_i, z_j) > \delta \) for any \( i \neq j \). We need a well-known result on decomposition of the unit ball \( \mathbb{B}_n \). The following version is Theorem 2.23 in [25].

**Lemma C.** There exists a positive integer \( N \) such that for any \( 0 < r < 1 \) we can find a sequence \( \{a_k\} \) in \( \mathbb{B}_n \) with the following properties:

(i) \( \mathbb{B}_n = \bigcup_k D(a_k, r) \).
(ii) The sets \( D(a_k, r/4) \) are mutually disjoint.
(iii) Each point \( z \in \mathbb{B}_n \) belongs to at most \( N \) of the sets \( D(a_k, 4r) \).

Any sequence \( \{a_k\} \) satisfying the conditions of the above lemma is called a lattice (or an \( r \)-lattice if one wants to stress the dependence on \( r \)) in the Bergman metric. Obviously any \( r \)-lattice is separated.

For convenience, we will denote by \( D_k = D(a_k, r) \) and \( \tilde{D}_k = D(a_k, 4r) \). Then Lemma C says that \( \mathbb{B}_n = \bigcup_{k=1}^\infty D_k \) and there is an positive integer \( N \) such that every point \( z \in \mathbb{B}_n \) belongs to at most \( N \) of sets \( \tilde{D}_k \).

We also need the following atomic decomposition theorem for weighted Bergman spaces. This turns out to be a powerful theorem in the theory of Bergman spaces. The result is basically due to Coifman and Rochberg [5], and can be found in Chapter 2 of [25].

**Theorem D.** Suppose \( p > 0 \), \( \alpha > -1 \), and
\[
b > n \max \left( 1, \frac{1}{p} \right) + 1 + \frac{1 + \alpha}{p}.
\]
Then we have

(i) For any separated sequence \( \{a_k\} \) in \( \mathbb{B}_n \) and any sequence \( \lambda = \{\lambda_k\} \in \ell^p \), the function
\[
f(z) = \sum_{k=1}^\infty \lambda_k \frac{(1 - |a_k|^2)^{b - (n+1+\alpha)/p}}{(1 - \langle z, a_k \rangle)^b}
\]
belongs to \( A^p_{\alpha} \) and
\[
\|f\|_{p, \alpha} \lesssim \|\{\lambda_k\}\|_{\ell^p}.
\]
(ii) If \( f \in A^p_{\alpha} \), then there is an \( r \)-lattice \( \{a_k\} \) in \( \mathbb{B}_n \) and a sequence \( \{\lambda_k\} \in \ell^p \) such that
\[
f(z) = \sum_{k=1}^\infty \lambda_k \frac{(1 - |a_k|^2)^{b - (n+1+\alpha)/p}}{(1 - \langle z, a_k \rangle)^b},
\]
and
\[
\|\{\lambda_k\}\|_{\ell^p} \lesssim \|f\|_{p, \alpha}.
\]

In the proof given in [25], part (i) requires that the sequence \( \{a_k\} \) is an \( r \)-lattice for some \( r \in (0, 1] \), but it is well known that only the separation of the sequence \( \{a_k\} \) is needed.

As was said before, the fact that, for \( 0 < q \leq 1 \), any function in the Bergman space \( A^q_{\beta} \) admits a weak factorization follows easily from part (ii) of Theorem D. Since in [25] it is only considered the case \( \alpha_1 = \alpha_2 = \beta \), we give the details. Indeed, let \( f \in A^p_{\beta} \) and take
\[
f_k(z) = \lambda_k \frac{(1 - |a_k|^2)^{\frac{1}{2} - (n+1+\alpha_1)/p_1}}{(1 - \langle z, a_k \rangle)^{b_1/2}}, \quad g_k(z) = \lambda_k \frac{(1 - |a_k|^2)^{\frac{1}{2} - (n+1+\alpha_2)/p_2}}{(1 - \langle z, a_k \rangle)^{b_2/2}},
\]
with $b$ big enough. Then $f = \sum_k f_k g_k$ and by Lemma \[8\] we have $\|f_k\|_{p_1, \alpha_1} \lesssim |\lambda_k|$ and $\|g_k\|_{p_2, \alpha_2} \leq C$. Since $0 < q \leq 1$, we have

$$
\sum_k \|f_k\|_{p_1, \alpha_1} \|g_k\|_{p_2, \alpha_2} \lesssim \sum_k |\lambda_k| \leq \|\{\lambda_k\}\|_{\ell^q} \lesssim \|f\|_{q, \beta}.
$$

Using the embedding of Hardy spaces into Bergman spaces together with the atomic decomposition for Bergman spaces, the proof of the weak factorization for $H^p$ with $0 < p < 1$ is surprisingly simple, so that we suspect that it must be known to the experts, but since we couldn’t find it in the literature it is included here. We refer to the books \[21\] and \[25\] for the theory of Hardy spaces in the unit ball.

**Theorem 4.** Let $0 < p < 1$, and $r, s$ such that $\frac{1}{p} = \frac{1}{r} + \frac{1}{s}$. If $f \in H^p$, then there are functions $f_j \in H^r$ and $g_j \in H^s$ such that

$$
f = \sum_j f_j g_j
$$

and

$$
\sum_j \|f_j\|_{H^r} \cdot \|g_j\|_{H^s} \leq C \|f\|_{H^p}.
$$

**Proof.** By Corollary 4.49 in \[25\], for $\alpha = \frac{n}{p} - (n + 1)$ we have $H^p \subset A^1_\alpha$ with $\|f\|_{1, \alpha} \leq C\|f\|_{H^p}$. Using the atomic decomposition for the Bergman space $A^1_\alpha$ we see that there is a sequence of points $\{a_k\} \subset \mathbb{B}_n$ such that any $f \in H^p$ admits the decomposition

$$
f(z) = \sum_k \lambda_k \frac{(1 - |a_k|^2)^{n/p}}{(1 - \langle z, a_k \rangle)^{2n/p}}
$$

with $\sum_k |\lambda_k| \leq C\|f\|_{H^p}$. Let

$$
f_k(z) = \lambda_k \frac{(1 - |a_k|^2)^{n/r}}{(1 - \langle z, a_k \rangle)^{2n/r}}, \quad \text{and} \quad g_k(z) = \frac{(1 - |a_k|^2)^{n/s}}{(1 - \langle z, a_k \rangle)^{2n/s}}.
$$

It is clear that $f = \sum_k f_k g_k$. Since $\|f_k\|_{H^r} = |\lambda_k|$ and $\|g_k\|_{H^s} = 1$ we are done. \[\Box\]

3. **Weak factorizations and Hankel forms**

The equivalence between boundedness of $T^{ao}_b$ and weak factorization can be formulated as the following result. The proof here basically follows the argument of Corollary 1.2 in \[1\].

**Proposition 5.** Let $1 < q < \infty$ and $\alpha, \beta > -1$. Let $p_1, p_2$ and $\alpha_1, \alpha_2$ satisfy \[3\] and \[7\], and let $q'$ and $\beta'$ satisfy \[1\]. The following are equivalent:

(i) $A^q_\beta = A^p_{\alpha_1} \odot A^p_{\alpha_2}$

(ii) For any analytic function $b$, $T^{ao}_b$ is bounded on $A^p_{\alpha_1} \times A^p_{\alpha_2}$ if and only if $b \in A^{q'}_{\beta'}$.

**Proof.** (ii)$\Rightarrow$(i). Assume that (ii) holds, we prove that

$$
(A^q_\beta)^* = (A^p_{\alpha_1} \odot A^p_{\alpha_2})^* \quad \text{with duality under the pairing } \langle \cdot, \cdot \rangle_\alpha.
$$

Since $A^q_\beta$ is reflexive and a Banach space $X$ is reflexive if and only if $X^*$ is reflexive \[22\], p.31], this would give (i). Let $F \in (A^q_\beta)^*$. By Theorem \[A\] there is a function $b \in A^{q'}_{\beta'}$ such that $F(\varphi) = \langle \varphi, b \rangle_\alpha$ for any $\varphi \in A^q_\beta$. By (ii),
we know that $T_b^\alpha$ is bounded on $A_{\alpha_1}^{p_1} \times A_{\alpha_2}^{p_2}$. Let $f \in A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2}$. Then, for any $\varepsilon > 0$, we can find two sequences $\{g_k\} \in A_{\alpha_1}^{p_1}$ and $\{h_k\} \in A_{\alpha_2}^{p_2}$ such that $f = \sum_k g_k h_k$, and

$$
\sum_{k=1}^\infty \|g_k\|_{A_{\alpha_1}^{p_1}} \|h_k\|_{A_{\alpha_2}^{p_2}} \leq \|f\|_{A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2}} + \varepsilon.
$$

Hence

$$
|F(f)| = |(f, b)_\alpha| = \left| \sum_{k=1}^\infty \langle g_k h_k, b \rangle_\alpha \right| = \left| \sum_{k=1}^\infty T_b^\alpha (g_k, h_k) \right| 
\leq |T_b^\alpha| \sum_{k=1}^\infty \|g_k\|_{A_{\alpha_1}^{p_1}} \|h_k\|_{A_{\alpha_2}^{p_2}} \leq \|T_b^\alpha\| \left( \|f\|_{A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2}} + \varepsilon \right).
$$

Since $\varepsilon > 0$ was arbitrary, we get that

$$
|F(f)| \leq |T_b^\alpha| \cdot \|f\|_{A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2}}.
$$

Thus $F \in (A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2})^*$, and so $(A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2})^* \subseteq (A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2})^*$.

On the other hand, suppose $F \in (A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2})^*$ with norm $\|F\|$. Then for all $\varphi \in A_{\alpha_2}^{p_2}$ we have

$$
|F(\varphi)| = |F(1 \cdot \varphi)| \leq \|F\| \cdot \|1\|_{p_1, \alpha_1} \cdot \|\varphi\|_{p_2, \alpha_2} = \|F\| \cdot \|\varphi\|_{p_2, \alpha_2}.
$$

Hence $F \in (A_{\alpha_2}^{p_2})^*$, and so, by Theorem $\Box$, there is an unique function $b \in A_{\alpha_2}^{p_2}$ such that $F(\varphi) = \langle \varphi, b \rangle_\alpha$ for all $\varphi \in A_{\alpha_2}^{p_2}$, where $p_2'$ and $\alpha_2'$ satisfy

$$
\frac{1}{p_2} + \frac{1}{p_2'} = 1, \quad \frac{\alpha_2}{p_2} + \frac{\alpha_2'}{p_2'} = \alpha.
$$

Now let $f = gh$ with $g \in A_{\alpha_1}^{p_1}$ and $h \in A_{\alpha_2}^{p_2}$. Then $f \in A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2}$. Since $F \in (A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2})^*$, we know that

$$
|T_b^\alpha (g, h)| = |(gh, b)_\alpha| = |(f, b)_\alpha| = |F(f)| 
\leq \|F\| \cdot \|f\|_{A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2}} \leq \|F\| \cdot \|g\|_{p_1, \alpha_1} \cdot \|h\|_{p_2, \alpha_2},
$$

which shows that $T_b^\alpha$ extends to a continuous linear functional on $A_{\alpha_1}^{p_1} \times A_{\alpha_2}^{p_2}$ with $\|T_b^\alpha\| \leq \|F\|$. By (ii) we know that $b \in A_{\alpha_2}^{p_2}$, hence $F \in (A_{\alpha_2}^{p_2})^*$. This shows that

$$
(A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2})^* \subseteq (A_{\alpha_2}^{p_2})^*.
$$

Combining the above arguments we know that (7) is true, and so (i) is true.

Next let us assume that (i) holds, and prove (ii). First, assume that $b \in A_{\alpha_2}^{p_2}$. A simple application of H"older’s inequality clearly shows that $T_b^\alpha$ is bounded on $A_{\alpha_1}^{p_1} \times A_{\alpha_2}^{p_2}$.

Conversely, assume that $T_b^\alpha$ is bounded on $A_{\alpha_1}^{p_1} \times A_{\alpha_2}^{p_2}$ with norm $\|T_b^\alpha\|$. Take any $f \in A_{\alpha_1}^{p_1}$. By (i) we know that $f \in A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2}$ and $\|f\|_{A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2}} \leq \|f\|_{q, \beta}$. Hence, for any $\varepsilon > 0$, we can find two sequences $\{g_k\} \in A_{\alpha_1}^{p_1}$ and $\{h_k\} \in A_{\alpha_2}^{p_2}$ such that $f = \sum_k g_k h_k$, and

$$
\sum_{k=1}^\infty \|g_k\|_{A_{\alpha_1}^{p_1}} \|h_k\|_{A_{\alpha_2}^{p_2}} \leq \|f\|_{A_{\alpha_1}^{p_1} \circ A_{\alpha_2}^{p_2}} + \varepsilon.
$$
Hence
\[
|\langle f, b \rangle_\alpha| = \left| \sum_{k=1}^{\infty} \langle g_k h_k, b \rangle_\alpha \right| = \left| \sum_{k=1}^{\infty} T^\alpha_b (g_k, h_k) \right| 
\leq \|T^\alpha_b\| \sum_{k=1}^{\infty} \|g_k\|_{A^p_{r_1}} \|h_k\|_{A^p_{r_2}} \leq \|T^\alpha_b\| (\|f\|_{A^p_{r_1}} \circ A^p_{r_2}) + \varepsilon.
\]

Since \(\varepsilon\) was arbitrary we get that
\[
|\langle f, b \rangle_\alpha| \leq \|T^\alpha_b\| \cdot \|f\|_{A^p_{r_1}} \circ A^p_{r_2} \lesssim \|T^\alpha_b\| \cdot \|f\|_{A^p_{r_3}} < \infty,
\]
and so by Theorem A, \(b \in (A^q_\beta)^* = A^q_{\beta/r'}\). The proof is complete. \(\square\)

4. PROOF OF THEOREM 3

In this section we prove Theorem 3, from which Theorem 2 follows. We first prove
an auxiliary result which may be of independent interest. Let \(b \geq 0\) and \(\alpha > -1\). For a
measurable function \(f\) on \(B_n\), we define the following integral operator
\[
R^{\alpha,b} f(z) = \int_{B_n} \frac{f(w)}{(1 - (z, w))^{n+1+\alpha+b}} dv_\alpha(w).
\]
The operator \(R^{\alpha,b}\) is the same as the one appearing in [25, Section 1.4], and is the unique
continuous linear operator on \(H(B_n)\), satisfying
\[
R^{\alpha,b} \left( \frac{1}{(1 - (z, w))^{n+1+\alpha+b}} \right) = \frac{1}{(1 - (z, w))^{n+1+\alpha+b}}
\]
for all \(w \in B_n\).

**Lemma 6.** Let \(b \geq 0\) be any fixed number. Let \(\alpha, \beta > -1, q > 1\) satisfy
\[
1 + \alpha > \frac{1 + \beta}{q}.
\]
Let \(f \in H(B_n)\). If there is a constant \(M > 0\) such that for any \(0 < r \leq 1\) and any \(r\)-lattice
\(\{a_k\}\) in \(B_n\),
\[
\sum_{k=1}^{\infty} |R^{\alpha,b} f(a_k)|^q (1 - |a_k|^2)^{b_q + (n+1+\beta)} \leq M^q,
\]
then \(f \in A^q_\beta\) and \(\|f\|_{q,\beta} \leq M\).

**Proof.** Suppose (9) holds. Choose \(\beta' = q'(\alpha - \beta/q)\) (which means \(\alpha = \beta/q + \beta'/q'\)).
Note that condition \(1 + \alpha > (1 + \beta)/q\) in the lemma guarantees that \(\beta' > -1\) by the
following computation:
\[
\frac{1 + \beta'}{q'} = (1 + \alpha) - \frac{1 + \beta}{q} > 0.
\]
Take any \(h \in A^q_{\beta'}\). Since
\[
b \geq 0 > -\frac{1 + \beta}{q} = \frac{1 + \beta'}{q'} - (1 + \alpha),
\]
we know that
\[
n + 1 + \alpha + b > n + \frac{1 + \beta'}{q'}.
\]
Hence, from Theorem D, we know that, there exists a sequence \( \{ \mu_k \} \in \ell^{q'} \) with \( \| \{ \mu_k \} \|_{\ell^{q'}} \leq \| h \|_{q', \beta'} \) and an r-lattice \( \{ a_k \} \) in \( \mathbb{Z}_n \) such that

\[
h(z) = \sum_{k=1}^{\infty} \mu_k \frac{(1 - |a_k|^2)^{(n+1+\alpha+\beta-(n+1+\beta')/q')}}{(1 - \langle z, a_k \rangle)^{(n+1+\alpha+\beta)}}.
\]

Hence

\[
\langle h, f \rangle = \int_{\mathbb{Z}_n} \sum_{k=1}^{\infty} \mu_k \frac{(1 - |a_k|^2)^{(n+1+\alpha+\beta-(n+1+\beta')/q')}}{(1 - \langle z, a_k \rangle)^{(n+1+\alpha+\beta)}} f(z) \, dv_\alpha(z)
\]

\[
= \sum_{k=1}^{\infty} \mu_k (1 - |a_k|^2)^{(n+1+\alpha+\beta-(n+1+\beta')/q')} R^{\alpha, b} f(a_k).
\]

Since

\[
n + 1 + \alpha + b - \frac{n + 1 + \beta'}{q'} = b + \frac{n + 1 + \beta}{q},
\]

by Theorem A and Hölder’s inequality we obtain

\[
\| f \|_{q, \beta} \lesssim \sup_{\| h \|_{q', \beta'} = 1} |\langle h, f \rangle| \lesssim \sup_{\| h \|_{q', \beta'} = 1} \left( \sum_{k=1}^{\infty} |\mu_k|^q \right)^{1/q} \left[ \sum_{k=1}^{\infty} (1 - |a_k|^2)^{(n+1+\alpha+\beta)} |R^{\alpha, b} f(a_k)|^q \right]^{1/q} \lesssim M,
\]

and so \( f \in A^q_\beta \). The proof is complete. \( \square \)

Now we are ready to prove Theorem 3.

Proof of Theorem 3. As we noticed before, we just need to prove that \( S_f^\alpha : A^p_{\alpha_1} \rightarrow A^p_{\alpha_2} \) is bounded if and only if \( f \in A^q_\beta \).

Suppose first that \( f \in A^q_\beta \). We need to show \( S_f^\alpha : A^p_{\alpha_1} \rightarrow A^p_{\alpha_2} \) is bounded. Let \( g \in A^p_{\alpha_1} \). If \( p_2 > 1 \) then \( P_\alpha : L^p(\mathbb{Z}_n, dv_{\alpha_2}) \rightarrow A^p_{\alpha_2} \) is bounded, and then from Hölder’s inequality the result follows. Indeed,

\[
\| S_f^\alpha g \|_{p_2, \alpha_2} = \| P_\alpha (fg) \|_{p_2, \alpha_2} \leq C \| fg \|_{p_2, \alpha_2} \leq C \| f \|_{q, \beta} \cdot \| g \|_{p_1, \alpha_1}
\]

which shows that \( S_f^\alpha : A^p_{\alpha_1} \rightarrow A^p_{\alpha_2} \) is bounded with

\[
\| S_f^\alpha \| \lesssim \| f \|_{q, \beta}.
\]

Conversely, suppose \( S_f^\alpha : A^p_{\alpha_1} \rightarrow A^p_{\alpha_2} \) is bounded, we are going to show that \( f \in A^q_\beta \).

We begin with using an argument of Luecking (see, e.g., [12]). Let \( r_k(t) \) be a sequence of Rademacher functions (see [8, Appendix A]). Let \( b \) be large enough so that

\[
(10) \quad b > n + \frac{1 + \alpha_1}{p_1}.
\]

Fix any \( r > 0 \), and let \( \{ a_k \} \) be an r-lattice and \( \{ D_k \} \) be the associated sets in Lemma 1. By Theorem D, we know that, for any sequence of real numbers \( \{ \lambda_k \} \in \ell^{p_1} \), the function

\[
g_t(z) = \sum_{k=1}^{\infty} \lambda_k r_k(t) \frac{(1 - |a_k|^2)^{(n+1+\alpha_1)/p_1}}{(1 - \langle z, a_k \rangle)^b}
\]

belongs to $A^p_{\alpha_1}$ with $\|g_t\|_{p_1,\alpha_1} \leq \|\{\lambda_k\}\|_{\ell^p}$ for almost every $t$ in $(0, 1)$. Denote by

$$g_k(z) = \frac{(1 - |a_k|^2)^{b-(n+1+\alpha_1)/p_1}}{(1 - \langle z, a_k \rangle)^b}. $$

Since $S^\varphi_j : A^p_{\alpha_1} \to A^p_{\alpha_2}$ is bounded, we get that

$$\|S^\varphi_j g_t\|_{p_2,\alpha_2}^p = \int_{B_n} \left| \sum_{k=1}^\infty \lambda_k r_k(t) S^\varphi_j g_k(z) \right|^{p_2} dv_{\alpha_2}(z) \leq \|S^\varphi_j\|_{p_2}^p : \|g_t\|_{p_1,\alpha_1}^p \leq \|S^\varphi_j\|_{p_2}^p : \|\{\lambda_k\}\|_{\ell^p}^p$$

for almost every $t$ in $(0, 1)$. Integrating both sides with respect to $t$ from 0 to 1, and using Fubini’s Theorem and Khinchine’s inequality (see [22, p.12]), we get

$$\int B_n \left( \sum_{k=1}^\infty |\lambda_k|^{p_2} |S^\varphi_j g_k(z)|^2 \right)^{p_2/2} dv_{\alpha_2}(z) \leq \|S^\varphi_j\|_{p_2}^p : \|\{\lambda_k\}\|_{\ell^p}^p. \tag{11}$$

Now we estimate

$$\sum_{k=1}^\infty |\lambda_k|^{p_2} \int_{D_k} |S^\varphi_j g_k(z)|^{p_2} dv_{\alpha_2}(z) = \int B_n \left( \sum_{k=1}^\infty |\lambda_k|^{p_2} |S^\varphi_j g_k(z)|^{p_2} \chi_{\tilde{D}_k}(z) \right)^{p_2/2} dv_{\alpha_2}(z). \tag{12}$$

If $p_2 \geq 2$, then $2/p_2 \leq 1$, and from (12) we have

$$\sum_{k=1}^\infty |\lambda_k|^{p_2} \int_{\tilde{D}_k} |S^\varphi_j g_k(z)|^{p_2} dv_{\alpha_2}(z) \leq \int B_n \left( \sum_{k=1}^\infty |\lambda_k|^2 |S^\varphi_j g_k(z)|^2 \chi_{\tilde{D}_k}(z) \right)^{p_2/2} dv_{\alpha_2}(z) \leq \int B_n \left( \sum_{k=1}^\infty |\lambda_k|^2 |S^\varphi_j g_k(z)|^2 \right)^{p_2/2} dv_{\alpha_2}(z).$$

If $1 < p_2 < 2$, then $2/p_2 > 1$, from Hölder’s inequality we get

$$\sum_{k=1}^\infty |\lambda_k|^{p_2} \int_{\tilde{D}_k} |S^\varphi_j g_k(z)|^{p_2} dv_{\alpha_2}(z) \leq \int B_n \left( \sum_{k=1}^\infty |\lambda_k|^2 |S^\varphi_j g_k(z)|^2 \right)^{p_2/2} \left( \sum_{k=1}^\infty \chi_{\tilde{D}_k}(z) \right)^{1-p_2/2} dv_{\alpha_2}(z) \leq N^{1-p_2/2} \int B_n \left( \sum_{k=1}^\infty |\lambda_k|^2 |S^\varphi_j g_k(z)|^2 \right)^{p_2/2} dv_{\alpha_2}(z),$$
since each \( z \in \mathbb{B}_n \) belongs to at most \( N \) of the sets \( \hat{D}_k \). Combining the above two inequalities, and applying (11) we obtain

\[
\sum_{k=1}^{\infty} |\lambda_k|^{p_2} \int_{\hat{D}_k} |S^\alpha f_k(z)|^{p_2} dv_{\alpha_2}(z)
\leq \min\{1, N^{1-p_2/2}\} \int_{\mathbb{B}_n} \left( \sum_{k=1}^{\infty} |\lambda_k|^{2} |S^\alpha f_k(z)|^{2} \right)^{p_2/2} dv_{\alpha_2}(z)
\lesssim \|S^\alpha f\|^{p_2} \cdot \|\{\lambda_k\}\|^{p_2}_{\ell^{p_1}}.
\]

By subharmonicity we know that,

\[
|S^\alpha f_k(a_k)|^{p_2} \lesssim \frac{1}{(1 - |a_k|^2)^{n+1+\alpha_2}} \int_{\hat{D}_k} |S^\alpha f_k(z)|^{p_2} dv_{\alpha_2}(z).
\]

From this we obtain

\[
(13) \quad \sum_{k=1}^{\infty} |\lambda_k|^{p_2} (1 - |a_k|^2)^{n+1+\alpha_2} |S^\alpha f_k(a_k)|^{p_2} \lesssim \|S^\alpha f\|^{p_2} \cdot \|\{\lambda_k\}\|^{p_2}_{\ell^{p_1}}.
\]

Let \( R^{\alpha,b} \) be the integral operator defined in (8). Then

\[
S^\alpha f_k(a_k) = \int_{\mathbb{B}_n} \frac{f(w)g_k(w)}{(1 - \langle a_k, w \rangle)^{n+1+\alpha}} dv_{\alpha}(w)
= \int_{\mathbb{B}_n} \frac{f(w)(1 - |a_k|^2)^{b-(n+1+\alpha_1)/p_1}}{(1 - \langle a_k, w \rangle)^{n+1+\alpha}(1 - \langle a_k, w \rangle)^{b+1+\alpha}} dv_{\alpha}(w)
= (1 - |a_k|^2)^{b-(n+1+\alpha_1)/p_1} \int_{\mathbb{B}_n} \frac{f(w)}{(1 - \langle a_k, w \rangle)^{n+1+\alpha+b}} dv_{\alpha}(w)
= (1 - |a_k|^2)^{b-(n+1+\alpha_1)/p_1} R^{\alpha,b} f(a_k).
\]

Thus (13) becomes

\[
\sum_{k=1}^{\infty} |\lambda_k|^{p_2} (1 - |a_k|^2)^{(n+1+\alpha_2)+b-(n+1+\alpha_1)/p_1}|R^{\alpha,b} f(a_k)|^{p_2} \lesssim \|S^\alpha f\|^{p_2} \cdot \|\{\lambda_k\}\|^{p_2}_{\ell^{p_1}}.
\]

Since

\[
(n + 1 + \alpha_2) + \left( b - \frac{n + 1 + \alpha_1}{p_1} \right) p_2 = \left( b + \frac{n + 1 + \beta}{q} \right) p_2,
\]

the equation (14) is the same as

\[
\sum_{k=1}^{\infty} |\lambda_k|^{p_2} \left[ (1 - |a_k|^2)^{b+(n+1+\beta)/q} R^{\alpha,b} f(a_k) \right]^{p_2} \lesssim \|S^\alpha f\|^{p_2} \cdot \|\{\lambda_k\}\|^{p_2}_{\ell^{p_1}}.
\]

Since \( \{\lambda_k^{p_2}\} \) was an arbitrary sequence in \( \ell^{p_1} \), we know that \( \{\lambda_k^{p_2}\} \) is an arbitrary sequence in \( \ell^{p_1/p_2} \). Since the conjugate exponent of \( p_1/p_2 \) is \( (p_1/p_2)' = p_1/(p_1 - p_2) \), by duality we obtain that

\[
\left\{ (1 - |a_k|^2)^{b+(n+1+\beta)/q} R^{\alpha,b} f(a_k) \right\} \in \ell^{p_1/p_2/(p_1 - p_2)} = \ell^q,
\]

and

\[
\sum_{k=1}^{\infty} (1 - |a_k|^2)^{bq+(n+1+\beta)} |R^{\alpha,b} f(a_k)|^q \lesssim \|S^\alpha f\|^q.
\]

Note that condition (6) guarantees that \( 1 + \alpha > (1 + \beta)/q \). Since (16) is true for any \( 0 < r \leq 1 \) and any \( r \)-lattice \( \{a_k\} \) in \( \mathbb{B}_n \), we can apply Lemma 6 to obtain that \( f \in A^q_\beta \) and
\[
\|f\|_{q,\beta} \lesssim \|S_f\|.
\]
This finishes the proof. \( \square \)

5. Further Results

5.1. Compactness. Under the assumptions of Theorem 3 actually one has that the small Hankel operator \( h^\alpha_f : A^p_{\alpha_1} \to \overline{A^p_{\alpha_2}} \) is bounded if and only if it is compact. This is from a general result of Banach space theory. It is known that, for \( 0 < p_2 < p_1 < \infty \), every bounded operator from \( \ell^{p_1} \) to \( \ell^{p_2} \) is compact (see, for example Theorem I.2.7, p.31 in [15]). Since the weighted Bergman space \( A^p_\alpha \) is isomorphic to \( \ell^p \) (see, Theorem 11, p.89 in [22]), note that the same proof there works for weighted Bergman spaces on the unit ball \( \mathbb{B}_n \), we get directly the above result.

5.2. Small Hankel operators with the same weights. In order to clarify the result on small Hankel operators between Bergman spaces given in Theorem 3 we consider the case of the same weights, that is, when \( \alpha_1 = \alpha_2 = \beta = \alpha \). In that case, all the restrictions in Theorem 3 reduces to \( p_2 > 1 \). We isolate this case here.

**Theorem 7.** Let \( \alpha > -1 \), \( 1 < p_2 < p_1 < \infty \) and \( f \in H(B_n) \). Then \( h^\alpha_f : A^p_{\alpha_1} \to \overline{A^p_{\alpha_2}} \) is bounded if and only if \( f \in A^q_\alpha \), with \( q = \frac{p_1 p_2}{p_1 - p_2} \).

This proves a conjecture in [4]. Concerning the boundedness of \( h^\alpha_f : A^p_{\alpha_1} \to \overline{A^p_{\alpha_2}} \) for all possible choices of \( 0 < p_1, p_2 < \infty \), we mention here that the case \( p_1 = p_2 > 1 \) is by now classical (see [13], [24] and [4]), and in this case the boundedness is equivalent to the symbol \( f \) being in the Bloch space \( \mathcal{B} \), that consists of those holomorphic functions \( f \) on \( \mathbb{B}_n \) with
\[
\|f\|_\mathcal{B} = |f(0)| + \sup_{z \in \mathbb{B}_n} (1 - |z|^2)|Rf(z)| < \infty.
\]
Here, \( Rf \) denotes the radial derivative of \( f \), that is,
\[
Rf(z) = \sum_{k=1}^n z_k \frac{\partial f}{\partial z_k}(z), \quad z = (z_1, \ldots, z_n) \in \mathbb{B}_n.
\]
The Bloch space also admits an equivalent norm in terms of the invariant gradient \( \nabla f(z) := \nabla(f \circ \varphi_z)(0) \) as follows
\[
\|f\|_\mathcal{B} \asymp |f(0)| + \sup_{z \in \mathbb{B}_n} |\nabla f(z)|.
\]
The case \( 0 < p_1 \leq p_2 \) is completely settled in [4] (actually the results are stated for the unweighted Bergman spaces \( A^p \), but the proofs works also for the weighted case). The description for the case \( p_1 = p_2 = 1 \) is that \( f \) must belong to the so called logarithmic Bloch space, a result that goes back to the one dimensional case obtained by Attele [2]. Concerning estimates with loss, in [4] Bonami and Luo obtained a description for the case \( 0 < p_2 < p_1 \) with \( p_2 < 1 \) (again the result in [4] is stated for the unweighted Bergman spaces). Thus, in view of our result, to complete the picture it remains to deal with the case \( p_1 > p_2 = 1 \) (this problem is also open for the unit disk). In that case, also in [4], some partial results are obtained (again for the unweighted case). Mainly, they provide a
pointwise estimate that is necessary for the small Hankel operator to be bounded, and they show that the condition

\begin{equation}
(f(z) \log \frac{2}{1-|z|})^p \in L^{p'}(B_n, dv_{\alpha})
\end{equation}

is sufficient. Moreover, they conjecture that the previous condition is also necessary. We have not been able to prove the conjecture, but we are going to shed some light on that problem.

**Theorem 8.** Let \( f \in H(B_n), \alpha > -1 \) and \( p_1 > 1 \). Let \( p'_1 \) be the conjugate exponent of \( p_1 \). Then \( h^{\Omega}_{p_1} : A^p_{p_1} \rightarrow A^p_{p'_1} \) is bounded if and only if the multiplication operator \( M_f : B \rightarrow A^{p'_1}_{p'_1} \) is bounded.

Before going to the proof we need first some preparation. First of all, recall that the Bloch space is the dual of \( A^1_{\alpha} \) under the integral pairing \( \langle , \rangle_{\alpha} \) (see [25, Theorem 3.17]). We also need the following lemma, whose one dimensional analogue is essentially proved in [3].

**Lemma 9.** Let \( 1 < p < \infty, \sigma > -1, \) and \( n + 1 + \sigma < b \). Then

\[
\int_{B_n} \frac{|f(z) - f(a)|^p}{|1 - \langle a, z \rangle|^t} \, dv_{\sigma}(z) \lesssim \int_{B_n} |z||f(z)|^p \, dv_{\sigma}(z)
\]

for any \( f \in H(B_n) \) and \( a \in B_n \).

**Proof.** We are going to prove first that, for \( 0 \leq t < n + 1 + \sigma \),

\begin{equation}
\int_{B_n} \frac{|f(z) - f(0)|^p}{|1 - \langle a, z \rangle|^t} \, dv_{\sigma}(z) \lesssim \int_{B_n} \frac{(1 - |w|^2)^p |Rf(w)|^p}{|1 - \langle a, w \rangle|^t} \, dv_{\sigma}(w).
\end{equation}

From [25, p.51], for \( \beta \) big enough, say \( \beta \geq 1 + \sigma \), we have

\[
|f(z) - f(0)| \leq C \int_{B_n} \frac{(1 - |w|^2)^p |Rf(w)|^p}{|1 - \langle a, w \rangle|^t} \, dv_{\sigma}(w).
\]

Take a small number \( \varepsilon > 0 \) with \( \sigma - \varepsilon \max(p, p') > -1 \), where \( p' \) denotes the conjugate exponent of \( p \), and \( t < n + 1 + \sigma - \varepsilon p \). An application of Hölder’s inequality and Lemma 3 yields

\[
|f(z) - f(0)|^p \lesssim (1 - |z|^2)^{-\varepsilon p} \int_{B_n} \frac{(1 - |w|^2)^p |Rf(w)|^p}{|1 - \langle a, w \rangle|^t} \, dv_{\sigma}(w).
\]

This together with Fubini’s theorem and [19, Lemma 2.5] gives

\[
\int_{B_n} \frac{|f(z) - f(0)|^p}{|1 - \langle a, z \rangle|^t} \, dv_{\sigma}(z) \\
\lesssim \int_{B_n} (1 - |w|^2)^p |Rf(w)|^p \left( \int_{B_n} \frac{dv_{\sigma-\varepsilon p}(z)}{|1 - \langle a, z \rangle|^t |1 - \langle a, w \rangle|^t} \right) \, dv_{\sigma-\varepsilon p}(w) \\
\lesssim \int_{B_n} (1 - |w|^2)^p |Rf(w)|^p \, dv_{\sigma}(w)
\]

proving (18). Now, a change of variables \( z = \varphi_{\alpha}(\zeta) \) gives (see [25, Proposition 1.13])

\[
\int_{B_n} \frac{|f(z) - f(a)|^p}{|1 - \langle a, z \rangle|^b} \, dv_{\sigma}(z) = \int_{B_n} \frac{|(f \circ \varphi_{\alpha})(\zeta) - (f \circ \varphi_{\alpha})(0)|^p}{|1 - \langle a, \varphi_{\alpha}(\zeta) \rangle|^b} \, dv_{\sigma}(\zeta).
\]
From [25, Lemma 1.3] we have

\[ 1 - \langle a, \varphi_a(\zeta) \rangle = 1 - \langle \varphi_a(0), \varphi_a(\zeta) \rangle = \frac{1 - |a|^2}{1 - \langle a, \zeta \rangle}. \]

Therefore we obtain

\[
\int_{B_n} \frac{|f(z) - f(a)|^p}{|1 - \langle a, z \rangle|^b} \, dv_\sigma(z) = (1 - |a|^2)^{n+1+\sigma-b} \int_{B_n} \frac{|(f \circ \varphi_a)(\zeta) - (f \circ \varphi_a)(0)|^p}{|1 - \langle a, \zeta \rangle|^{2(n+1+\sigma-b)}} \, dv_\sigma(\zeta).
\]

Due to our condition \( b > n + 1 + \sigma \), we have

\[ t = 2(n + 1 + \sigma) - b < n + 1 + \sigma \]

and we can apply (13) to get

\[
\int_{B_n} \frac{|f(z) - f(a)|^p}{|1 - \langle a, z \rangle|^b} \, dv_\sigma(z) \lesssim (1 - |a|^2)^{n+1+\sigma-b} \int_{B_n} \frac{(1 - |\zeta|^2)^p |R(f \circ \varphi_a)(\zeta)|^p}{|1 - \langle a, \zeta \rangle|^{2(n+1+\sigma-b)}} \, dv_\sigma(\zeta).
\]

Since

\[ (1 - |\zeta|^2)^p |R(f \circ \varphi_a)(\zeta)| \leq |\nabla f(\varphi_a)\rangle |\nabla f(\varphi_a)(\zeta)| = |\nabla f(\varphi_a)\rangle |, \]

another change of variables \( w = \varphi_a(\zeta) \) finally gives

\[
\int_{B_n} \frac{|f(z) - f(a)|^p}{|1 - \langle a, z \rangle|^b} \, dv_\sigma(z) \lesssim \int_{B_n} \frac{|\nabla f(w)|^p}{|1 - \langle a, w \rangle|^b} \, dv_\sigma(w).
\]

completing the proof of the lemma. \( \square \)

After these preparations, we are now ready for the proof of Theorem [8]

**Proof of Theorem [8]** Assume first that the small Hankel operator \( h_{\alpha}^f : A^p_{\alpha} \to \overline{A}^1 \) is bounded. Let \( g \in A^p_{\alpha} \). From the pointwise estimate for Bergman spaces, we get

\[ |\langle g, f \rangle_\alpha| = |h_{\alpha}f(0)| \leq C \|h_{\alpha}f\|_{1,\alpha} \leq C \|h_{\alpha}f\| \cdot \|g\|_{p_1,\alpha}. \]

Therefore, by duality, we have that \( f \in A^p_{\alpha} \) with

\[ \|f\|_{p_1,\alpha} \leq C \|h_{\alpha}^f\|. \]

Recall that \( h_{\alpha}^f : A^p_{\alpha} \to \overline{A}^1 \) is bounded, if and only if, \( S^f_\alpha : A^p_{\alpha} \to A^1_\alpha \) is bounded, with \( \|S^f_\alpha\| \approx \|h_{\alpha}^f\| \). Also, since for any \( g \in A^p_{\alpha} \) and \( h \in B \),

\[ \langle S^f_\alpha g, h \rangle_\alpha = \langle f, gh \rangle_\alpha = \langle S^f_\alpha h, g \rangle_\alpha \]

we know that \( S^f_\alpha : B \to A^p_{\alpha} \) is bounded, and moreover, we have

\[ \|S^f_\alpha\|_{B \to A^p_{\alpha}} \lesssim \|h_{\alpha}^f\|. \]

For \( g \) in the Bloch space \( B \), one has

\[ \|Mfg\|_{p_1,\alpha}^p = \int_{B_n} |f(z)\overline{g(z)}|^{p_1} \, dv_\alpha(z) \]

\[
\lesssim \int_{B_n} |S^f_\alpha g(z)|^{p_1} \, dv_\alpha(z) + \int_{B_n} |f(z)\overline{g(z)} - S^f_\alpha g(z)|^{p_1} \, dv_\alpha(z).
\]

Due to the boundedness of \( S^f_\alpha : B \to A^p_{\alpha} \),

\[ \int_{B_n} |S^f_\alpha g(z)|^{p_1} \, dv_\alpha(z) \leq \|S^f_\alpha\|_{B \to A^p_{\alpha}} \cdot \|g\|^p_{B} \lesssim \|h_{\alpha}^f\|^{p_1} \cdot \|g\|_{B}^{p_1}. \]
On the other hand, by the reproducing formula for Bergman spaces and Hölder’s inequality,

\[ |f(z) - S_f^\rho g(z)|_{|z|^p_1} \leq \left| \int_{\mathbb{B}_n} f(w) \frac{g(z) - g(w)}{(1 - \langle z, w \rangle)^{n+1+\alpha}} \, dv_\alpha(w) \right|_{|z|^p_1} \]

\[ \leq \left( \int_{\mathbb{B}_n} \frac{|f(w)|_{|z|^p_1}}{|1 - \langle w, z \rangle|^{n+1+\alpha}} \, dv_\alpha(\varepsilon^p_{\rho}) \right) \left( \int_{\mathbb{B}_n} \frac{|g(z) - g(w)|_{|z|^p_1}}{|1 - \langle w, z \rangle|^{n+1+\alpha}} \, dv_\alpha_{\varepsilon^p_{\rho}}(w) \right)^{\rho_1_{|z|^p_1}}, \]

where \( \varepsilon > 0 \) satisfies \( \alpha - \varepsilon \max(p_1, \rho_1) > -1 \). Using Lemma 9 and Lemma B we get

\[ \int_{\mathbb{B}_n} \frac{|g(z) - g(w)|_{|z|^p_1}}{|1 - \langle w, z \rangle|^{n+1+\alpha}} \, dv_\alpha_{\varepsilon^p_{\rho}}(w) \lesssim \int_{\mathbb{B}_n} \frac{\|g\|_{B}^p_1 (1 - |z|^2)^{-\varepsilon p_1}}{\|z\|^p_1} \]

Therefore, this together with Fubini’s theorem, Lemma B and the estimate (19) gives

\[ \int_{\mathbb{B}_n} \frac{|f(z) - S_f^\rho g(z)|_{|z|^p_1}}{dv_\alpha(z)} \leq C\|g\|_{B}^p_1 \int_{\mathbb{B}_n} |f(w)|_{|z|^p_1} \left( \int_{\mathbb{B}_n} \frac{dv_\alpha_{\varepsilon^p_{\rho}}(z)}{|1 - \langle w, z \rangle|^{n+1+\alpha}} \right) \, dv_\alpha(\varepsilon^p_{\rho}) \]

\[ \leq C\|g\|_{B}^p_1 \cdot \|f\|_{P_\alpha}^p_{\rho} \leq C\|h_f^\alpha\|_{B} \cdot \|g\|_{B}^p_1. \]

Putting together the estimates (21), (22) and (23) it follows that \( M_f : B \to A^\rho_\alpha^p \) is bounded with \( \|M_f\|_{B \to A^\rho_\alpha^p} \lesssim \|h_f^\alpha\|_{B}. \)

Conversely, suppose that \( M_f : B \to A^\rho_\alpha^p \) is bounded. By the boundedness of the projection \( P_\alpha : L^p_\alpha(\mathbb{B}_n, dv_\alpha) \to A^\rho_\alpha^p \) one deduces that \( S_f^\rho : B \to A^\rho_\alpha^p \) is also bounded, and so obviously, \( S_f^\rho : B_0 \to A^\rho_\alpha^p \) is bounded, where \( B_0 \) is the little Bloch space, and it is well-known that the dual space of \( B_0 \) is \( A^1_\alpha \) under the integral pair \((\cdot, \cdot)_\alpha\) (see, for example, Chapter 3 of [25]), from (20) we know that \( S_f^\rho : A^\rho_\alpha^p \to A^1_\alpha \) is bounded. \( \Box \)

As a consequence of Theorem 8 we can easily obtain the sufficient and necessary conditions given in (13) as well as another relevant necessary condition for the boundedness of \( h_f^\alpha : A^p_\alpha \to A^1_\alpha \).

**Corollary 10.** Let \( f \in H(\mathbb{B}_n), \alpha > -1 \) and \( p_1 > 1 \).

(i) If (17) holds, then \( h_f^\alpha : A^p_\alpha \to A^1_\alpha \) is bounded.

(ii) If \( h_f^\alpha : A^p_\alpha \to A^1_\alpha \) is bounded, then

\[ \sup_{z \in \mathbb{B}_n} (1 - |z|^2)^{(n+1+\alpha)/p_1} |f(z)| \left( \log \frac{2}{1 - |z|^2} \right)^{\rho_1} < \infty \]

and

\[ \int_{\mathbb{B}_n} |f(z)|^p_1 \left( \log \frac{2}{1 - |z|^2} \right)^{\rho_1} \, dv_\alpha(z) < \infty. \]
Proof. Part (i) follows directly from Theorem 8 and the pointwise estimate for Bloch functions
\[ |g(z)| \leq \|g\|_B \log \frac{2}{1 - |z|^2}. \]
To prove part (ii), for each \( z \in \mathbb{B}_n \), the function
\[ g_z(w) = \log \frac{2}{1 - \langle w, z \rangle} \]
is in the Bloch space with \( \|g_z\|_B \leq C \) with the constant \( C \) independent of the point \( z \). Therefore, from the pointwise estimate for functions in Bergman spaces, we get
\[
(1 - |z|^2)^{n+1+\alpha} \left( |f(z)| \log \frac{2}{1 - |z|^2} \right)^{p'_1} = (1 - |z|^2)^{n+1+\alpha} |f(z) g_z(z)|^{p'_1} \\
\leq \|fg_z\|_{p'_1,\alpha} = \|M_f g_z\|_{p'_1,\alpha} \\
\leq \|M_f\|_{B \rightarrow A^{p'_1}_{\alpha}} \cdot \|g_z\|_{B}^{p'_1} \lesssim \|M_f\|_{B \rightarrow A^{p'_1}_{\alpha}},
\]
and (24) follows due to Theorem 8. The necessity of (25) is also a consequence of Theorem 8. Indeed, clearly \( M_f : B \rightarrow A^{p'_1}_{\alpha} \) is bounded if and only if the measure
\[
d\mu_f(z) = |f(z)|^{p'_1} dv_n(z)
\]
is a \( p'_1 \)-Carleson measure for the Bloch space (see [7, 10] for the definition); and by Proposition 1.4 in [7] (the one dimensional case appears in [10] and [14]) this implies (25), finishing the proof. \( \square \)

The established connection between Hankel operators on Bergman spaces and Carleson measures for the Bloch space makes even more interesting the problem (as far as we know, still open) of describing those measures.

REFERENCES

[1] N. Arcozzi, R. Rochberg, E. Sawyer and B. D. Wick, Bilinear forms on the Dirichlet space, Anal. PDE 3 (2010), 21–47.
[2] K. Attele, Toeplitz and Hankel operators on Bergman one space, Hokkaido Math. J. 21 (1992), 279–293.
[3] D. Blasi and J. Pau, A characterization of Besov type spaces and applications to Hankel type operators, Michigan Math. J. 56 (2008), 401-417.
[4] A. Bonami and L. Luo, On Hankel operators between Bergman spaces on the unit ball, Houston J. Math. 31 (2005), 815–828.
[5] R. Coifman and R. Rochberg, Representation theorems for holomorphic and harmonic functions in \( L^p \), Asterisque 77 (1980), 11-66.
[6] R. Coifman, R. Rochberg and G. Weiss, Factorization theorems for Hardy spaces in several variables, Ann. of Math. (2) 103 (1976), 611–635.
[7] E. Doubtsov, Carleson-Sobolev measures for weighted Bloch spaces, J. Funct. Anal. 258 (2010), 2801–2816.
[8] P.L. Duren, ‘Theory of \( H^p \) Spaces’, Academic Press, New York-London 1970. Reprint: Dover, Mineola, New York 2000.
[9] J. Garnett and R. Latter, The atomic decomposition for Hardy spaces in several complex variables, Duke Math. J. 45 (1978), 815–845.
[10] D. Girela, J. A. Peláez, F. Pérez-González and J. Rättyä, Carleson measures for the Bloch space, Integral Equations and Operator Theory 61 (2008), 511–547.
[11] M. Gowda, Nonfactorization theorems in weighted Bergman and Hardy spaces on the unit ball of \( \mathbb{C}_n \), Trans. Amer. Math. Soc. 277 (1983), 203–212.
[12] C. Horowitz, Factorization theorems for functions in the Bergman spaces, Duke Math. J., 44 (1977), 201–213.
[13] S. Janson, J. Peetre and R. Rochberg, Hankel forms and the Fock space, Revista Mat. Iberoamericana 3 (1987), 61–138.
[14] T.G. Limperis, ‘Embedding theorems for the Bloch space’, PhD thesis, University of Arkansas, 1998.
[15] J. Lindenstrauss and L. Tzafriri, ‘Classical Banach Spaces’, Lecture Notes in Math. 338, Springer-Verlag, Berlin, 1973.

[16] D. H. Luecking, Representations and duality in weighted spaces of analytic functions, Indiana Univ. Math. J. 34 (1985) 319–336.

[17] D. H. Luecking, Embedding theorems for spaces of analytic functions via Khinchine’s inequality, Michigan Math. J. 40 (1993), 333–358.

[18] D. H. Luecking, Representations and duality in weighted spaces of analytic functions, J. Func. Anal., 73 (1987), 345–368.

[19] Z. Nehari, On bounded bilinear forms, Ann. of Math. (2) 65 (1957), 153–162.

[20] J.M. Ortega and J. Fabrega, Pointwise multipliers and corona type decomposition in BMOA, Ann. Inst. Fourier (Grenoble) 46 (1996), 111–137.

[21] R. Rochberg, Decomposition theorems for Bergman spaces and their applications, in ‘Operators and Function Theory’, D. Reidel, 1985, 225–277.

[22] W. Rudin, ‘Function Theory in the Unit Ball of $\mathbb{C}^n$’, Springer, New York, 1980.

[23] P. Wojtaszczyk, ‘Banach Spaces for Analysts’, Cambridge Studies in Advanced Mathematics 25. Cambridge University Press, 1991.

[24] R. Zhao and K. Zhu, ‘Theory of Bergman spaces in the unit ball of $\mathbb{C}^n$’, Mem. Soc. Math. Fr. (N.S.), 115 (2008), vi+103 pp.

[25] K. Zhu, Hankel operators on the Bergman spaces of bounded symmetric domains, Trans. Amer. Math. Soc. 324 (1991), 707–730.

[26] K. Zhu, ‘Spaces of Holomorphic Functions in the Unit Ball’, Springer-Verlag, New York, 2005.

[27] K. Zhu, ‘Operator Theory in Function Spaces’, Second Edition, American Mathematical Society, Providence, Rhode Island, 2007.

JORDI PAU, DEPARTAMENT DE MATEMÀTICA APPLICADA I ANALISI, UNIVERSITAT DE BARCELONA, 08007 BARCELONA, SPAIN
E-mail address: jordi.pau@ub.edu

RUHAN ZHAO, DEPARTMENT OF MATHEMATICS, SUNY BROCKPORT, BROCKPORT, NY 14420, USA
E-mail address: rzhao@brockport.edu