

SECOND QUANTIZATION AND THE L^p -SPECTRUM OF NONSYMMETRIC ORNSTEIN-UHLENBECK OPERATORS

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ABSTRACT. The spectra of the second quantization and the symmetric second quantization of a strict Hilbert space contraction are computed explicitly and shown to coincide. As an application, we compute the spectrum of the nonsymmetric Ornstein-Uhlenbeck operator L associated with the infinite-dimensional Langevin equation

$$dU(t) = AU(t) dt + dW(t)$$

where A is the generator of a strongly continuous semigroup on a Banach space E and W is a cylindrical Wiener process in E . Assuming the existence of an invariant measure μ for L , under suitable assumptions on A we show that the spectrum of L in the space $L^p(E, \mu)$ ($1 < p < \infty$) is given by

$$\sigma(L) = \overline{\left\{ \sum_{j=1}^n k_j z_j : k_j \in \mathbb{N}, z_j \in \sigma(A_\infty); j = 1, \dots, n; n \geq 1 \right\}},$$

where A_∞ is the generator of a Hilbert space contraction semigroup canonically associated with A and μ . We prove that the assumptions on A are always satisfied in the strong Feller case and in the finite-dimensional case. In the latter case we recover the recent Metafuno-Pallara-Priola formula for $\sigma(L)$.

1. INTRODUCTION

There has been a considerable recent interest in the spectral theory of second order elliptic operators L of the form

$$(1.1) \quad L\phi(x) = \frac{1}{2} \text{Tr}(Q(x)D^2\phi(x)) + \langle A(x), D\phi(x) \rangle \quad (x \in E)$$

with unbounded drift term A on a finite or infinite dimensional space E ; see for example [12, 18, 19, 20]. In many situations L admits a unique invariant measure μ , in which case it is natural to consider the realization of L in the space $L^p(E, \mu)$; see [1, 4, 8, 11] and the references cited there. Even in space dimension one this class of operators is not completely understood at present.

In this paper we consider the case of nonsymmetric Ornstein-Uhlenbeck operators, i.e., the special case of (1.1) where $Q(x) = Q$ (the ‘diffusion’) is a fixed positive symmetric operator from E^* into E and $A(x) = Ax$ with A (the ‘drift’) an infinitesimal generator of a strongly continuous semigroup of operators on E . The state space E is allowed to be an arbitrary real Banach space, the operator Q is not assumed to have finite trace and the operator A may be unbounded. We

2000 *Mathematics Subject Classification*. Primary: 35R15, 81S10; Secondary: 35P05, 47D03, 47D07, 60H15.

Key words and phrases. Symmetric Fock space, second quantization, nonsymmetric Ornstein-Uhlenbeck operators, L^p -spectrum, invariant measure, reproducing kernel Hilbert spaces, strong Feller property.

This work was supported by ARC Discovery Grant DP0346406 and by a ‘VIDI subsidie’ in the ‘Vernieuwingsimpuls’ programme of the Netherlands Organization for Scientific Research (NWO).

do not assume that L is symmetric. Nonsymmetric Ornstein-Uhlenbeck operators arise, e.g., in Nonequilibrium Statistical Physics [5] and in the theory of stochastic partial differential equations; cf. [10, 11] and the references cited there.

Assuming the existence of an invariant measure μ for L , our aim is to determine the spectrum of L in $L^p(E, \mu)$ for $p \in (1, \infty)$. Let us recall that in $E = \mathbb{R}^d$, the ‘classical’ Ornstein-Uhlenbeck operator with $Q = I$ and $A = -I$,

$$L\phi(x) = \frac{1}{2}\Delta\phi(x) - \langle x, \nabla\phi(x) \rangle \quad (x \in \mathbb{R}^d)$$

which arises in Quantum Field Theory as the boson number operator, has a unique Gaussian invariant measure μ and the $L^p(\mathbb{R}^d, \mu)$ -spectrum of L is given by

$$\sigma(L) = \{-n : n \in \mathbb{N}\}$$

where $\mathbb{N} = \{0, 1, 2, \dots\}$. This formula is an easy consequence of the description of L as a second quantized operator [17, 22, 25] and can be extended without much difficulty to the case where E is a Hilbert space and A is selfadjoint with compact resolvent. The nonsymmetric case is considerably more difficult, however, even for $E = \mathbb{R}^d$. Under suitable nondegeneracy assumptions it was shown recently by Metafuno, Pallara and Priola [19] that in the case of $E = \mathbb{R}^d$ we have

$$(1.2) \quad \sigma(L) = \left\{ \sum_{i=1}^n k_i z_i : k_i \in \mathbb{N}, z_i \in \sigma(A); i = 1, \dots, n; n \geq 1 \right\}.$$

Their proof depends on a careful analysis of the smoothing effects of the transition semigroup $P = \{P(t)\}_{t \geq 0}$ generated by L . We will give a completely different proof of an infinite dimensional version of (1.2) which instead exploits the fact that the transition semigroup can be represented as the symmetric second quantization of the adjoint of an appropriate nonsymmetric contraction semigroup $S_\infty = \{S_\infty(t)\}_{t \geq 0}$ acting on the reproducing kernel Hilbert space of the invariant measure μ . The crucial step in this approach is to obtain a formula for the spectrum of the symmetric second quantization of Hilbert space contractions T . For strict contractions T this problem is solved completely. The main difficulty consists of showing that the spectra of the n -fold tensor product and the symmetric n -fold tensor product of T coincide and are given by

$$\sigma(T^{\otimes n}) = \sigma(T^{\otimes n}) = \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(T); j = 1, \dots, n \right\},$$

the second equality being a classical result due to Brown and Percy [6]. This easily implies equality of the spectra of the second quantization and the symmetric second quantization of T :

$$\sigma(\Gamma^{\otimes}(T)) = \sigma(\Gamma(T)) = \{1\} \cup \bigcup_{n \geq 1} \overline{\left\{ \prod_{j=1}^n z_j : z_j \in \sigma(T); j = 1, \dots, n \right\}}.$$

As a result we are able to compute the spectra of the operators $P(t)$ in $L^2(E, \mu)$ under the assumption that S_∞ is a semigroup of strict contractions. By combining these arguments with standard hypercontractivity results we obtain the spectra of $P(t)$ in $L^p(E, \mu)$ for all $p \in (1, \infty)$. The spectrum of L in $L^p(E, \mu)$ is then obtained via spectral mapping techniques. For this step we require that, in addition to being strictly contractive, S_∞ is also eventually norm continuous. Our main result asserts

that under these assumptions (which are shown to be automatically satisfied in two important cases: the strong Feller case and the finite dimensional case), we have

$$\sigma(L) = \overline{\left\{ \sum_{i=1}^n k_j z_j : k_j \in \mathbb{N}, z_j \in \sigma(A_\infty); j = 1, \dots, n; n \geq 1 \right\}}.$$

Here, A_∞ denotes the generator of the semigroup S_∞ . If S_∞ is compact (which is the case in the strong Feller case and in finite dimensions), no closure needs to be taken and we obtain

$$(1.3) \quad \sigma(L) = \left\{ \sum_{i=1}^n k_j z_j : k_j \in \mathbb{N}, z_j \in \sigma(A_\infty); j = 1, \dots, n; n \geq 1 \right\}.$$

In finite dimensions, under a nondegeneracy assumption we have $\sigma(A_\infty) = \sigma(A)$ and (1.3) reduces to the Metafuno-Pallara-Priola formula (1.2).

Acknowledgments - This work was done while the author stayed at the University of New South Wales. He thanks his colleagues at the School of Mathematics, especially Ben Goldys and Ian Doust, for their kind hospitality. This paper owes its existence to the numerous inspiring discussions with Ben Goldys who also pointed out the crucial references [16] and [23]. The author thanks Marco Furfman and Sylvania Pereira for helpful comments.

2. PRELIMINARIES

In this section we collect some well known results on spectra, strongly continuous semigroups, and reproducing kernel Hilbert spaces. For more detailed information we refer to [2], [3] and [13].

2.1. Spectral theory. Let X be a real or complex Banach space. The spectrum and resolvent set of a bounded or unbounded linear operator T on X will be denoted by $\sigma(T)$ and $\varrho(T)$, respectively. The spectral radius of a bounded operator T is denoted by $r(T)$. When X is a real Banach space, the spectrum of T is defined as the spectrum of its complexification.

The following result is true in the more general context of Banach algebras. By $\delta(K, L)$ we denote the Hausdorff distance between the compact sets $K, L \subseteq \mathbb{C}$.

Lemma 2.1 ([2, Theorem 3.4.1]). *For any two bounded operators S and T on X satisfying $ST = TS$ we have*

$$\delta(\sigma(S), \sigma(T)) \leq r(S - T).$$

We will apply this result in the following situation. Let $(X_n)_{n \geq 0}$ be a sequence of nonzero complemented subspaces of X such that $X_n \cap X_m = \{0\}$ for all $n, m \geq 0$ with $n \neq m$. Let $(\pi_n)_{n \geq 0}$ be a corresponding sequence of projections. For each $n \geq 0$ let $P_n := \bigoplus_{j=0}^n \pi_j$. Let T be a bounded operator on X which commutes with each P_n . We define operators T_n on X and S_n on X_n by $T_n := T \circ P_n$ and $S_n := T|_{X_n}$.

Proposition 2.2. *Under the above assumptions, if*

$$(2.1) \quad \lim_{n \rightarrow \infty} \|T - T_n\| = 0,$$

then

$$(2.2) \quad \sigma(T) = \overline{\bigcup_{n=0}^{\infty} \sigma(T_n)} = \overline{\bigcup_{n=0}^{\infty} \sigma(S_n)}.$$

Proof. Let $Y_n := \ker P_n = (I - P_n)X$. Then we have a direct sum decomposition $X = X_0 \oplus \cdots \oplus X_n \oplus Y_n$, relative to which we have $T_n = S_0 \oplus \cdots \oplus S_n \oplus 0$. From this we easily infer that $\sigma(T_n) = \{0\} \cup \bigcup_{j=0}^n \sigma(S_j)$. Moreover, from $\lim_{n \rightarrow \infty} \|S_n\| = \lim_{n \rightarrow \infty} \|T_n - T_{n-1}\| = 0$ we obtain that $0 \in \overline{\bigcup_{n \geq 0} \sigma(S_n)}$. The second identity in (2.2) immediately follows. The inclusion ‘ \subseteq ’ in the first identity follows from (2.1) and Lemma 2.1, while the inclusion ‘ \supseteq ’ follows from the obvious inclusions $\sigma(T_n) \subseteq \sigma(T)$. \square

An alternative proof of this result could be given with the Banach algebra techniques developed in [23].

Let X and Y be Banach spaces and let $X \widehat{\otimes} Y$ denote the completion of $X \otimes Y$ with respect to a uniform cross norm. If S and T are bounded operators on X and Y respectively, then the operator $S \otimes T$ defined on $X \otimes Y$

$$(S \otimes T)(x \otimes y) := (Sx \otimes Ty)$$

uniquely extends to a bounded operator $S \widehat{\otimes} T$ on $X \widehat{\otimes} Y$ of norm $\|S \widehat{\otimes} T\| \leq \|S\| \|T\|$. The spectrum of $S \widehat{\otimes} T$ is given by the following result, due to Schechter [24]. We will only need the Hilbert space version of it, which was obtained earlier by Brown and Pearcy [6].

Lemma 2.3. *We have $\sigma(S \widehat{\otimes} T) = \{\eta \cdot \zeta : \eta \in \sigma(S), \zeta \in \sigma(T)\}$.*

We continue with a brief discussion on the fine structure of the spectrum. The *point spectrum* of a bounded operator T is the set $\sigma_p(T)$ of its eigenvalues. The *approximate point spectrum* of T is the set $\sigma_a(T) = \mathbb{C} \setminus C$, where C is the set of all $z \in \mathbb{C}$ for which there is a constant $c > 0$ with $\|(z - T)x\| \geq c\|x\|$ for all $x \in X$. Notice that $z \in \sigma_a(T)$ if and only if there exists a sequence $(x_n)_{n \geq 1}$ of unit vectors such that $\lim_{n \rightarrow \infty} zx_n - Tx_n = 0$ strongly. Such a sequence is called an *approximate eigenvector* for z . In particular we see that $\sigma_p(T) \subseteq \sigma_a(T)$. Furthermore we always have $\partial\sigma(T) \subseteq \sigma_a(T)$, where $\partial\sigma(T)$ denotes the topological boundary of $\sigma(T)$. The *residual point spectrum* of T is the set $\sigma_r(T)$ of all $z \in \sigma(T)$ for which the range of $z - T$ is a proper, closed subspace of X . It follows from the Hahn-Banach theorem that every $z \in \sigma_r(T)$ is an eigenvalue of the adjoint operator T^* . Notice that $\sigma(T) = \sigma_a(T) \cup \sigma_r(T)$ and that the union is disjoint.

2.2. Semigroups of operators. Let A be the infinitesimal generator of a strongly continuous semigroup $T = \{T(t)\}_{t \geq 0}$ of bounded linear operators on X . The *spectral mapping theorem for the point spectrum* asserts that

$$\exp(t\sigma_p(A)) = \sigma_p(T(t)) \setminus \{0\} \quad \text{for all } t \geq 0.$$

The semigroup T is said to satisfy the *spectral mapping theorem* if

$$\exp(t\sigma(A)) = \sigma(T(t)) \setminus \{0\} \quad \text{for all } t \geq 0.$$

Every eventually norm continuous semigroup satisfies the spectral mapping theorem [13, Theorem IV.3.10]. Recall that T is *eventually norm continuous* if there exists a $t_0 \geq 0$ such that $t \mapsto T(t)$ is norm continuous for $t > t_0$. Compact semigroups and analytic semigroups are norm continuous for $t > 0$.

We will also need the following result [13, Theorem II.4.18].

Lemma 2.4. *If A is the infinitesimal generator of an eventually norm continuous semigroup T on X , then for every $a \in \mathbb{R}$ the set*

$$\{z \in \mathbb{C} : z \in \sigma(A), \operatorname{Re} z \geq a\}$$

is bounded.

2.3. Reproducing kernel Hilbert spaces. The material of this subsection is needed in Section 5. Let E be a real Banach space with dual E^* and let $Q \in \mathcal{L}(E^*, E)$ be a positive and symmetric linear operator, i.e., we have $\langle Qx^*, x^* \rangle \geq 0$ for all $x^* \in E^*$ and $\langle Qx^*, y^* \rangle = \langle Qy^*, x^* \rangle$ for all $x^*, y^* \in E^*$. On the range of Q , the bilinear mapping $(Qx^*, Qy^*) \mapsto \langle Qx^*, y^* \rangle$ defines an inner product. The completion of the range of Q with respect to this inner product is a real Hilbert space, the *reproducing kernel Hilbert space* associated with Q , notation: H_Q . The inclusion mapping from the range of Q into E extends to a continuous inclusion mapping $i_Q : H_Q \hookrightarrow E$. Upon identifying H_Q and its dual in the canonical way we have the operator identity

$$(2.3) \quad Q = i_Q \circ i_Q^*.$$

If $Q_1, Q_2 \in \mathcal{L}(E^*, E)$ are positive and symmetric operators, then we have $H_{Q_1} \subseteq H_{Q_2}$ as subsets of E if and only if there exists a constant $K \geq 0$ such that

$$(2.4) \quad \langle Q_1 x^*, x^* \rangle \leq K \langle Q_2 x^*, x^* \rangle \quad \text{for all } x^* \in E^*$$

in which case the inclusion mapping $H_{Q_1} \hookrightarrow H_{Q_2}$ is continuous.

If $i : H \hookrightarrow E$ is a continuous embedding of a real Hilbert space H into E , then $Q := i \circ i^*$ is positive and symmetric and its reproducing kernel space H_Q equals H . More precisely, the mapping $i^* x^* \mapsto i_Q^* x^*$ defines an isometry from H onto H_Q and from $i \circ i^* = Q = i_Q \circ i_Q^*$ we have $H = H_Q$ as subsets of E .

Examples of positive symmetric operators arise naturally in the theory of Gaussian distributions. Recall that if γ is a centred Gaussian Radon measure on E , then there exists a unique positive and symmetric operator $Q_\gamma \in \mathcal{L}(E^*, E)$, the *covariance operator* of γ , such that the Fourier transform of γ is given by

$$\widehat{\gamma}(x^*) := \int_E \exp(-i \langle x, x^* \rangle) d\gamma(x) = \exp(-\frac{1}{2} \langle Q_\gamma x^*, x^* \rangle) \quad \text{for all } x^* \in E^*.$$

In this situation the reproducing kernel Hilbert space $H_\gamma := H_{Q_\gamma}$ is separable, the embedding $i_\gamma : H_\gamma \hookrightarrow E$ is compact, and we have $\gamma(\overline{H_\gamma}) = 1$, the closure being taken with respect to the norm of E .

3. THE SPECTRUM OF SECOND QUANTIZED OPERATORS

Let H be a nonzero complex Hilbert space. For $n \geq 0$ we let $H^{\otimes n} = H \widehat{\otimes} \dots \widehat{\otimes} H$ be the n -fold Hilbert tensor product of H , with the understanding that $H^{\otimes 0} = \mathbb{C}$. The Hilbert space direct sum

$$\Gamma(H) := \bigoplus_{n \geq 0} H^{\otimes n}$$

is called the *Fock space* over H . The theory of Fock spaces is developed systematically in [22].

Given a bounded operator $T \in \mathcal{L}(H)$, we use the notation $T^{\otimes n} = T \widehat{\otimes} \cdots \widehat{\otimes} T \in \mathcal{L}(H^{\otimes n})$, with the understanding that $T^{\otimes 0} = I$. For later use we note that for all $S, T \in \mathcal{L}(H)$ and all $n \geq 1$ we have

$$(3.1) \quad \|T^{\otimes n}\|_{\mathcal{L}(H^{\otimes n})} = \|T\|^n$$

and, by a simple telescoping argument,

$$(3.2) \quad \|T^{\otimes n} - S^{\otimes n}\|_{\mathcal{L}(H^{\otimes n})} \leq \|T - S\| \cdot \sum_{j=0}^{n-1} \|S\|^j \|T\|^{n-1-j}.$$

If T is a contraction, the direct sum operator

$$\Gamma(T) := \bigoplus_{n \geq 0} T^{\otimes n}$$

is well defined and defines a contraction on $\Gamma(H)$. This operator is called the *second quantization* of T . We have the following algebraic relations:

$$(3.3) \quad \Gamma(I) = I, \quad \Gamma(T_1 T_2) = \Gamma(T_1) \Gamma(T_2), \quad \Gamma(T^*) = (\Gamma(T))^*.$$

Proposition 3.1. *If $\|T\| < 1$, then*

$$\sigma(\Gamma(T)) = \{1\} \cup \overline{\bigcup_{n \geq 1} \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(T); j = 1, \dots, n \right\}}.$$

Proof. Clearly, $\sigma(T^{\otimes 0}) = \{1\}$, whereas for $n \geq 1$ by repeated application of Lemma 2.3 we have

$$(3.4) \quad \sigma(T^{\otimes n}) = \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(T); j = 1, \dots, n \right\}.$$

If $\|T\| < 1$, then from (3.1) we see that the sum defining $\Gamma(T)$ converges in the operator norm. Hence, by Proposition 2.2,

$$\sigma(\Gamma(T)) = \{1\} \cup \overline{\bigcup_{n \geq 1} \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(T); j = 1, \dots, n \right\}}.$$

But from $r(T) \leq \|T\| < 1$ we see that 1 is an isolated point of $\sigma(\Gamma(T))$. \square

For our applications in the next sections we will be interested in the *symmetric Fock space* over H . This is the Hilbert space direct sum

$$\Gamma^{\otimes}(H) := \bigoplus_{n \geq 0} H^{\otimes n},$$

where $H^{\otimes n}$ denotes the closed subspace of $H^{\otimes n}$ spanned by all symmetric n -tensors, again with the understanding that $H^{\otimes 0} = \mathbb{C}$. If T is a bounded operator on H , then $T^{\otimes n}$ maps $H^{\otimes n}$ into itself. The restriction of $T^{\otimes n}$ to $H^{\otimes n}$ will be denoted by $T^{\otimes n}$. If T is a contraction, we define the *symmetric second quantization* of T by

$$\Gamma^{\otimes}(T) := \bigoplus_{n \geq 0} T^{\otimes n}.$$

Of course, $\Gamma^{\otimes}(T)$ is just the restriction of $\Gamma(T)$ to $\Gamma^{\otimes}(H)$. The algebraic relations (3.3) carry over in the obvious way.

Let S_n denote the permutation group on n elements. Given an element $h \in H$, the *creation operators* $a_n^\dagger(h) : H^{\otimes n} \rightarrow H^{\otimes(n+1)}$ are defined by

$$\begin{aligned} a_n^\dagger(h) & \sum_{\sigma \in S_n} g_{\sigma(1)} \otimes \cdots \otimes g_{\sigma(n)} \\ & := \frac{1}{\sqrt{n+1}} \sum_{\sigma \in S_n} \sum_{m=1}^{n+1} g_{\sigma(1)} \otimes \cdots \otimes g_{\sigma(m-1)} \otimes h \otimes g_{\sigma(m)} \otimes \cdots \otimes g_{\sigma(n)}, \end{aligned}$$

and the *annihilation operators* $a_{n+1}(h) : H^{\otimes(n+1)} \rightarrow H^{\otimes n}$ by

$$\begin{aligned} a_{n+1}(h) & \sum_{\sigma \in S_{n+1}} g_{\sigma(1)} \otimes \cdots \otimes g_{\sigma(n+1)} \\ & := \frac{1}{\sqrt{n+1}} \sum_{\sigma \in S_{n+1}} \sum_{m=1}^{n+1} [g_{\sigma(m)}, h]_H g_{\sigma(1)} \otimes \cdots \otimes g_{\sigma(m-1)} \otimes g_{\sigma(m+1)} \otimes \cdots \otimes g_{\sigma(n+1)}. \end{aligned}$$

These operators well defined and bounded, and their operator norms bounded by

$$(3.5) \quad \|a_n^\dagger\|_{\mathcal{L}(H^{\otimes n}, H^{\otimes(n+1)})} = \|a_{n+1}(h)\|_{\mathcal{L}(H^{\otimes(n+1)}, H^{\otimes n})} \leq C_n \|h\|$$

with constants C_n depending on n only. The first equality follows from the duality relations

$$(3.6) \quad a_n^{\dagger*}(h) = a_{n+1}.$$

Furthermore, we have the commutation relations

$$(3.7) \quad a_{n+2}(h)a_{n+1}^\dagger(h) - a_n^\dagger(h)a_{n+1}(h) = \|h\|^2 I.$$

For the proofs we refer to [22]. An obvious consequence of (3.6) and (3.7) is the lower bound

$$(3.8) \quad \|a_n^\dagger(h)g\|_{H^{\otimes(n+1)}}^2 \geq \|g\|_{H^{\otimes n}}^2 \|h\|^2.$$

We will need the following result from the theory of several complex variables, known as Hartog's theorem [15, page 106], cf. also [23, Lemma 2]:

Lemma 3.2. *Let K be a bounded set in \mathbb{C}^n , $n \geq 2$, and suppose that f is analytic in a neighbourhood of K . If $f(p) = z$ for some point $p \in K$, then there exists a point $p' \in \partial K$, the topological boundary of K , such that $f(p') = z$.*

We are now in a position to prove the following result.

Theorem 3.3. *For all $n \geq 0$ we have*

$$\sigma(T^{\otimes n}) = \sigma(T^{\otimes n}) = \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(T); j = 1, \dots, n \right\}.$$

In the proof below, and in the rest of the paper, we economize on brackets; for instance, $T^{\otimes n*}$ means $(T^{\otimes n})^*$ and $T^{*\otimes n}$ means $(T^*)^{\otimes n}$.

Proof. The second equality has already been noted in (3.4), so we concentrate on the proof that $\sigma(T^{\otimes n}) = \sigma(T^{\otimes n})$. For $n = 0$ this is trivial, so we fix $n \geq 1$.

In order to prove the inclusion $\sigma(T^{\otimes n}) \subseteq \sigma(T^{\otimes n})$ it suffices to check that $T^{\otimes n}$ maps $(H^{\otimes n})^\perp$ into itself. For any elementary symmetric tensor $h \in H^{\otimes n}$, say

$$h = \sum_{\sigma \in S_n} h_{\sigma(1)} \otimes \cdots \otimes h_{\sigma(n)},$$

and any element $x \in H^{\otimes n}$ we have

$$(3.9) \quad [h, T^{\otimes n} x]_{H^{\otimes n}} = \left[\sum_{\sigma \in S_n} T^* h_{\sigma(1)} \otimes \cdots \otimes T^* h_{\sigma(n)}, x \right]_{H^{\otimes n}} = [T^{*\otimes n} h, x]_{H^{\otimes n}}.$$

Clearly, $H^{\otimes n}$ is invariant under $T^{*\otimes n}$, and therefore for $x \in (H^{\otimes n})^\perp$ we obtain $[h, T^{\otimes n} x]_{H^{\otimes n}} = [T^{*\otimes n} h, x]_{H^{\otimes n}} = 0$. Thus, $T^{\otimes n} x \in (H^{\otimes n})^\perp$.

Next we prove the inclusion $\sigma(T^{\otimes n}) \subseteq \sigma(T^{\otimes n})$. We proceed by induction on n , the case $n = 1$ being trivial since $T^{\otimes 1} = T^{\otimes 1} = T$. Assume that we already know that $\sigma(T^{\otimes n}) \subseteq \sigma(T^{\otimes n})$ and fix $z \in \sigma(T^{\otimes(n+1)})$. We have to show that $z \in \sigma(T^{\otimes(n+1)})$.

Noting that $T^{\otimes(n+1)} = T^{\otimes n} \widehat{\otimes} T$, by Lemma 2.3 we have $z = \zeta \cdot \eta$ with $\zeta \in \sigma(T^{\otimes n}) \subseteq \sigma(T^{\otimes n})$ and $\eta \in \sigma(T)$. By Lemma 3.2 we may assume that $(\zeta, \eta) \in \partial(\sigma(T^{\otimes n}) \times \sigma(T))$, so $\zeta \in \partial\sigma(T^{\otimes n})$ or $\eta \in \partial\sigma(T)$.

Case 1: Assume that $\zeta \in \partial\sigma(T^{\otimes n})$ and $\eta \in \sigma_a(T)$. Since boundary spectrum belongs to the approximate point spectrum we have $\zeta \in \sigma_a(T^{\otimes n})$. Let $(g_k)_{k \geq 1}$ and $(h_k)_{k \geq 1}$ be corresponding approximate eigenvectors for $T^{\otimes n}$ and T , respectively. From $T^{\otimes(n+1)} a_n^\dagger(h_k)g_k = a_n^\dagger(T h_k)T^{\otimes n} g_k$ we have

$$\begin{aligned} & \|T^{\otimes(n+1)} a_n^\dagger(h_k)g_k - \zeta \eta a_n^\dagger(h_k)g_k\|_{H^{\otimes(n+1)}} \\ & \leq \|a_n^\dagger(T h_k)T^{\otimes n} g_k - \eta a_n^\dagger(T h_k)g_k\|_{H^{\otimes(n+1)}} \\ & \quad + \|\eta a_n^\dagger(T h_k)g_k - \zeta \eta a_n^\dagger(h_k)T g_k\|_{H^{\otimes(n+1)}} \\ & = \|a_n^\dagger(T h_k)(T^{\otimes n} g_k - \eta g_k)\|_{H^{\otimes(n+1)}} + |\eta| \|a_n^\dagger(T h_k - \zeta h_k)g_k\|_{H^{\otimes(n+1)}}. \end{aligned}$$

Hence, by (3.5) and since by assumption we have $\|g_k\|_{H^{\otimes n}} = \|h_k\| = 1$,

$$\lim_{k \rightarrow \infty} \|T^{\otimes(n+1)} a_n^\dagger(h_k)g_k - \zeta \eta a_n^\dagger(h_k)g_k\|_{H^{\otimes(n+1)}} = 0.$$

Moreover, by (3.8),

$$\|a_n^\dagger(h_k)g_k\|_{H^{\otimes(n+1)}} \geq \|g_k\|_{H^{\otimes n}} \|h_k\| = 1.$$

Since by (3.5) the sequence $(a_n^\dagger(h_k)g_k)_{k \geq 1}$ is also bounded, upon normalizing we obtain an approximate eigenvector for $T^{\otimes(n+1)}$ with approximate eigenvalue $z = \zeta \cdot \eta$.

Case 2: Assume that $\zeta \in \partial\sigma(T^{\otimes n})$ and $\eta \in \sigma_r(T)$. Then also $\zeta \in \partial\sigma(T^{\otimes n*})$ and hence $\zeta \in \sigma_a(T^{\otimes n*}) = \sigma_a(T^{*\otimes n})$. Also, $\eta \in \sigma_a(T^*)$, and therefore $z \in \sigma_a(T^{*\otimes(n+1)}) = \sigma_a(T^{\otimes(n+1)*}) \subseteq \sigma(T^{\otimes(n+1)})$ as in Case 1. Here we used that for all $k \geq 1$ we have $T^{\otimes k*} = T^{*\otimes k}$ by (3.9).

Case 3: If $\zeta \in \sigma_a(T^{\otimes n})$ and $\eta \in \partial\sigma(T)$ we proceed as in Case 1.

Case 4: If $\zeta \in \sigma_r(T^{\otimes n})$ and $\eta \in \partial\sigma(T)$ we proceed as in Case 2. \square

Arguing as in the proof of Proposition 3.1 we now obtain:

Theorem 3.4. *If $\|T\| < 1$, then*

$$\sigma(\Gamma^{\otimes}(T)) = \sigma(\Gamma(T)) = \{1\} \cup \overline{\bigcup_{n \geq 1} \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(T); j = 1, \dots, n \right\}}.$$

If T is compact, this result simplifies as follows:

Corollary 3.5. *If T is compact and satisfies $\|T\| < 1$, then*

$$\sigma(\Gamma^{\otimes}(T)) = \sigma(\Gamma(T)) = \{0\} \cup \{1\} \cup \bigcup_{n \geq 1} \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(T); j = 1, \dots, n \right\}.$$

Proof. We have already seen that $\sigma(\Gamma^{\otimes}(T)) = \sigma(\Gamma(T))$; for the second identity we have to show that $0 \in \sigma(\Gamma(T))$ and to prove the inclusion ‘ \subseteq ’.

From $\|T\| < 1$ and $\sigma(T) \neq \emptyset$ we see that 0 is in the closure of $\bigcup_{n \geq 1} \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(T); j = 1, \dots, n \right\}$. Hence, $0 \in \sigma(\Gamma(T))$ by Proposition 3.1.

From (3.1) and the compactness of $T^{\otimes n}$ we see that $\Gamma(T)$ is compact. Hence, $\sigma(\Gamma(T)) \setminus \{0\} = \sigma_p(\Gamma(T)) \setminus \{0\}$. Let $z \in \sigma(\Gamma(T)) \setminus \{0\}$ be arbitrary and choose an eigenvector x for z . Then for all $n \geq 1$ we have

$$T^{\otimes n} P_n x = P_n \Gamma(T) x = z P_n x,$$

where P_n denotes the orthogonal projection in $\Gamma(H)$ onto $\bigoplus_{0 \leq j \leq n} H^{\otimes j}$. For sufficiently large n we have $P_n x \neq 0$, and for those n we conclude that $z \in \sigma_p(T^{\otimes n})$. In particular we see that $z = \prod_{j=1}^n z_j$ for certain $z_j \in \sigma(T)$. \square

4. THE L^p -SPECTRUM OF SECOND QUANTIZED CONTRACTION SEMIGROUP GENERATORS

Throughout this section we fix an arbitrary real Banach space E and a centred Gaussian Radon measure γ on E . Let H_γ denote the reproducing kernel Hilbert space of γ and let $i_\gamma : H_\gamma \hookrightarrow E$ be the associated embedding. Since $\gamma(\overline{H_\gamma}) = 1$, when considering the spaces $L^p(E, \gamma)$ there will be no loss of generality in assuming that γ is *nondegenerate*, by which we mean that H_γ is dense in E .

Let $H := H_{\gamma, \mathbb{C}}$ be the complexification of H_γ . It is well known that the complex Hilbert space $L^2(E, \gamma)$ is canonically isometrically isomorphic to the symmetric Fock space $\Gamma^{\otimes}(H)$. We will describe this isometry briefly here; for a more detailed discussion we refer to [17]. Each element $h \in H_\gamma$ of the form $h = i_\gamma^* x^*$ defines a real-valued function $\phi_h \in L^2(E, \gamma)$ by $\phi_h(x) := \langle x, x^* \rangle$ and we have

$$\|\phi_h\|_{L^2(E, \gamma)}^2 = \int_E \langle x, x^* \rangle^2 d\gamma(x) = \|i_\gamma^* x^*\|_{H_\gamma}^2.$$

Since i_γ^* has dense range in H_γ , the mapping $h \mapsto \phi_h$ uniquely extends to an isometry from H_γ into the real part of $L^2(E, \gamma)$. By complexification we obtain an isometry $h \mapsto \phi_h$ from H into $L^2(E, \gamma)$. Using this isometry, for each $n \geq 1$ we define $\mathcal{H}_{\leq n}$ as the closed subspace of $L^2(E, \gamma)$ spanned by the constant one function $\mathbf{1}$ and all products $\phi_{h_1} \cdots \phi_{h_m}$ of order $1 \leq m \leq n$, where $h_1, \dots, h_n \in H$. We then let $\mathcal{H}_0 := \mathbb{C}\mathbf{1}$ and define, for $n \geq 1$, the space \mathcal{H}_n as the orthogonal complement of $\mathcal{H}_{\leq n-1}$ in $\mathcal{H}_{\leq n}$. The complex form of the Wiener-Itô decomposition theorem asserts that we have an orthogonal direct sum decomposition

$$L^2(E, \gamma) = \bigoplus_{n \geq 0} \mathcal{H}_n.$$

The space \mathcal{H}_n is usually referred to as the n -th *Wiener-Itô chaos*. Denoting by I_n the orthogonal projection in $L^2(E, \gamma)$ onto \mathcal{H}_n , it is not difficult to show that

$$\langle I_n(\phi_{h_1} \cdots \phi_{h_n}), I_n(\phi_{k_1} \cdots \phi_{k_n}) \rangle = \sum_{\sigma \in S_n} [h_1, k_{\sigma(1)}]_H \cdots [h_n, k_{\sigma(n)}]_H.$$

This shows that \mathcal{H}_n is canonically isometric to $H^{\otimes n}$ as a Hilbert space, the isometry being given explicitly by

$$I_n(\phi_{h_1} \cdots \phi_{h_n}) \mapsto \frac{1}{\sqrt{n!}} \sum_{\sigma \in S_n} h_{\sigma(1)} \otimes \cdots \otimes h_{\sigma(n)}.$$

Thus the Wiener-Itô decomposition induces a canonical isometry of $L^2(E, \gamma)$ and the symmetric Fock space $\Gamma^{\otimes}(H)$.

Let us now assume that A is the infinitesimal generator of a strongly continuous semigroup of contractions $S = \{S(t)\}_{t \geq 0}$ on H . We denote by $P_2 = \{P_2(t)\}_{t \geq 0}$ its symmetric second quantization:

$$P_2(t) = \Gamma^{\otimes}(S(t)).$$

By the isometry just described, P_2 induces a semigroup of contractions, also denoted by P_2 , on $L^2(E, \gamma)$. Since P_2 is strongly continuous on each \mathcal{H}_n , it follows that P_2 is strongly continuous on $L^2(E, \gamma)$. In fact, P_2 is doubly Markovian and therefore P_2 extends uniquely to a strongly continuous semigroup of contractions on $L^p(E, \gamma)$ for every $p \in [1, \infty)$; cf. [25].

Lemma 4.1. *If $t \mapsto S(t)$ is norm continuous for $t > t_0$ and $S(t)$ is a strict contraction for $t > s_0$, then for every $p \in (1, \infty)$, $t \mapsto P_p(t)$ is norm continuous for $t > \max\{t_0, s_0\}$.*

Proof. First we consider the case $p = 2$. By (3.2), for each $n \geq 1$ the restriction $P_{2,n}$ of P_2 to \mathcal{H}_n is contractive and norm continuous for $t > t_0$. For $t > s_0$, by (3.1) we have $P_2(t) = \sum_{n \geq 0} P_{2,n}(t)$ with convergence in the operator norm, uniformly on $[s, \infty)$ for every $s > s_0$. Hence, for $t > \max\{t_0, s_0\}$ the function $t \mapsto P_2(t)$ is norm continuous, since on this interval it is the locally uniform limit of a sequence norm continuous functions.

Next we take $p \in (1, 2)$ and use the fact that $\|P_1(t) - P_1(s)\|_{\mathcal{L}(L^1(E, \gamma))} \leq 2$ and the Riesz-Thorin interpolation theorem to find that

$$\|P_p(t) - P_p(s)\|_{\mathcal{L}(L^p(E, \gamma))} \leq 2^{1-\theta_p} \|P_2(t) - P_2(s)\|_{\mathcal{L}(L^2(E, \gamma))}^{\theta_p}$$

where $(1-\theta_p) + \frac{1}{2}\theta_p = \frac{1}{p}$. For $p \in (2, \infty)$ we proceed similarly, this time interpolating between $L^2(E, \gamma)$ and $L^{p'}(E, \gamma)$ with $p' \in (p, \infty)$. \square

In the next lemma we need some further results about the spaces $L^p(E, \gamma)$. We refer to [17] for the proofs, which are based on standard hypercontractivity arguments. For all $p \in (1, \infty)$ and $n \geq 0$ we have $\mathcal{H}_n \subseteq L^p(E, \gamma)$ and the restrictions of the $L^2(E, \gamma)$ -norm and the $L^p(E, \gamma)$ -norm are equivalent on \mathcal{H}_n . Furthermore, the orthogonal projections I_n in $L^2(E, \gamma)$ onto \mathcal{H}_n extend uniquely to projections $I_{p,n}$ in $L^p(E, \gamma)$ onto \mathcal{H}_n . As a subspace of $L^p(E, \gamma)$, \mathcal{H}_n will be denoted by $\mathcal{H}_{p,n}$. By the observations just made, each $\mathcal{H}_{p,n}$ is complemented in $L^p(E, \gamma)$.

Lemma 4.2. *For all $p \in (1, \infty)$ there is a constant $\theta_p \in (0, 1]$ such that for all $n \geq 1$ and $t \geq 0$ we have*

$$\|P_{p,n}(t)\|_{\mathcal{L}(\mathcal{H}_{p,n})} \leq \|S(t)\|^{n\theta_p}.$$

As a consequence we have

$$(4.1) \quad P_p(t) = \sum_{n \geq 0} P_{p,n}(t),$$

the convergence being in the operator norm, uniformly on $[t_0, \infty)$ for all $t_0 > 0$.

Proof. Fix $t \geq 0$. For $p = 2$ we may take $\theta_p = 1$. For $p \in (1, 2)$, choose $p' \in (1, p)$ and recall that $P_{p'}$ is a contraction semigroup on $L^{p'}(E, \gamma)$. In particular, by taking restrictions, we see that $\|P_{p',n}(t)\|_{\mathcal{L}(\mathcal{H}_{p',n})} \leq 1$ for all $n \geq 1$. Since we also have $\|P_{2,n}(t)\|_{\mathcal{L}(\mathcal{H}_n)} = \|S(t)\|^n$, for $p \in (1, 2)$ the result now follows by interpolation; notice that $(\mathcal{H}_n, \mathcal{H}_{p',n})_{\theta_p} = \mathcal{H}_{p,n}$ with $\frac{1}{p'}(1 - \theta_p) + \frac{1}{2}\theta_p = \frac{1}{p}$. For $p \in (2, \infty)$ we proceed similarly, this time interpolation between \mathcal{H}_n and $\mathcal{H}_{p',n}$ with $p' \in (p, \infty)$.

By the estimate just proved, the series in (4.1) $\sum_{n \geq 0} P_{p,n}(t)$ converges in the operator norm, uniformly on $[t_0, \infty)$ for every $t_0 > 0$. Moreover, on the dense subspace spanned by the spaces $\mathcal{H}_{p,n}$ the sum equals $P_p(t)$. This proves (4.1). \square

The infinitesimal generators of the semigroups P_p and $P_{p,n}$ will be denoted by L_p and $L_{p,n}$, respectively. We are now ready to state and prove the main result of this section. Let us call a strongly continuous semigroup T *strictly contractive* if $\|T(t)\| < 1$ for all $t > 0$.

Theorem 4.3. *Let $p \in (1, \infty)$. If S is strictly contractive and eventually norm continuous, then*

$$(4.2) \quad \begin{aligned} \sigma(L_{p,0}) &= \{0\}, \\ \sigma(L_{p,n}) &= \overline{\left\{ \sum_{j=1}^n \zeta_j : \zeta_j \in \sigma(A); j = 1, \dots, n \right\}} \quad (n \geq 1), \end{aligned}$$

and

$$(4.3) \quad \begin{aligned} \sigma(L_p) &= \overline{\left\{ \sum_{j=1}^n \zeta_j : \zeta_j \in \sigma(A); j = 1, \dots, n \right\}} \\ &= \overline{\left\{ \sum_{j=1}^n k_j z_j : k_j \in \mathbb{N}, z_j \in \sigma(A); j = 1, \dots, n; n \geq 1 \right\}}. \end{aligned}$$

Proof. Let $p \in (1, \infty)$ be fixed.

It is clear that $\sigma(L_{p,0}) = \{0\}$, so let us fix $n \geq 1$.

From Theorem 3.3, Lemma 4.1, and the spectral mapping theorem for eventually norm continuous semigroups, first applied to $P_{p,n}$ and then to S , we obtain that for all $t \geq 0$,

$$(4.4) \quad \begin{aligned} \exp(t \sigma(L_{p,n})) &= \sigma(P_{p,n}(t)) \setminus \{0\} \\ &= \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(S(t)); j = 1, \dots, n \right\} \setminus \{0\} \\ &= \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(S(t)) \setminus \{0\}; j = 1, \dots, n \right\} \\ &= \left\{ \prod_{j=1}^n \exp(t \zeta_j) : \zeta_j \in \sigma(A); j = 1, \dots, n \right\} \\ &= \left\{ \exp\left(t \sum_{j=1}^n \zeta_j\right) : \zeta_j \in \sigma(A); j = 1, \dots, n \right\}. \end{aligned}$$

In order to obtain the corresponding equality for $\sigma(L_p)$ we first check that for all $t \geq 0$,

$$(4.5) \quad \sigma(P_p(t)) = \{1\} \cup \overline{\bigcup_{n \geq 1} \left\{ \prod_{j=1}^n z_j : z_j \in \sigma(S(t)); j = 1, \dots, n \right\}}.$$

Clearly this holds for $t = 0$, and for fixed $t > 0$ this follows from Proposition 2.2, Theorem 3.3, (4.1), and the fact that $\mathcal{H}_n = \mathcal{H}_{p,n}$ with equivalent norms. Repeating the argument of (4.4) we obtain

$$(4.6) \quad \exp(t\sigma(L_p)) = \{1\} \cup \overline{\bigcup_{n \geq 1} \left\{ \exp\left(t \sum_{j=1}^n \zeta_j\right) : \zeta_j \in \sigma(A); j = 1, \dots, n \right\} \setminus \{0\}}.$$

Let

$$B_n = \left\{ \sum_{j=1}^n \zeta_j : \zeta_j \in \sigma(A); j = 1, \dots, n \right\} \quad (n \geq 1)$$

and

$$B := \bigcup_{n \geq 1} \left\{ \sum_{j=1}^n \zeta_j : \zeta_j \in \sigma(A); j = 1, \dots, n \right\}.$$

For (4.2) we have to prove the inclusions $B_n \subseteq \sigma(L_{p,n})$ and $\sigma(L_{p,n}) \subseteq B_n$; for (4.3) we have to prove the inclusions $\overline{B} \subseteq \sigma(L_p)$ (the inclusion $\{0\} \subseteq \sigma(L)$ being trivial) and $\sigma(L_p) \setminus \{0\} \subseteq \overline{B}$. We shall prove the latter two; the former two are proved in the same way. We adapt an argument from [16].

- $\overline{B} \subseteq \sigma(L_p)$:

Since $\sigma(L_p)$ is closed, it suffices to prove that $B \subseteq \sigma(L_p)$. Fix an arbitrary $\zeta \in B$, say $\zeta = \sum_{j=1}^n \zeta_j$ with $n \geq 1$ and $\zeta_j \in \sigma(A)$ ($j = 1, \dots, n$). By (4.6), for every $t > 0$ we find an element $\zeta(t) \in \sigma(L_p)$ and integer $N(t) \in \mathbb{Z}$ such that

$$(4.7) \quad \zeta = 2\pi i t^{-1} N(t) + \zeta(t).$$

From $\operatorname{Re} \zeta(t) = \operatorname{Re} \zeta$ and Lemma 2.4 we see that there is a constant $C \geq 0$ such that $|\operatorname{Im} \zeta(t)| \leq C$ for all $t > 0$. Comparing imaginary parts in (4.7) and letting $t \downarrow 0$ we see that $N(t) = 0$ for small enough t . For those t we then have $\zeta = \zeta(t) \in \sigma(L_p)$.

- $\sigma(L_p) \setminus \{0\} \subseteq \overline{B}$:

The proof proceeds along the same lines, but extra care is needed to control the number of terms occurring in the sums defining the elements of B . Fix $z \in \sigma(L_p) \setminus \{0\}$. Since $\|S(t)\| < 1$ for all $t > 0$, standard arguments from semigroup theory imply that S is uniformly exponentially stable. Choose $\omega > 0$ and $M \geq 1$ such that $\|S(t)\| \leq M e^{-\omega t}$ for all $t \geq 0$. Then, $\sigma(A) \subseteq \{\lambda \in \mathbb{C} : \operatorname{Re} \lambda \leq -\omega\}$. Together with (4.6) this implies that $\operatorname{Re} z \leq -\omega$. By Lemma 2.4, there exists a constant $C \geq 1$ such that for every $w \in \sigma(A)$ satisfying $\operatorname{Re} w \geq 2\operatorname{Re} z$ we have $|\operatorname{Im} w| \leq C$. In particular,

$$(4.8) \quad |\operatorname{Im} z| \leq C.$$

For reasons that will become clear in a moment we fix $t_0 > 0$ subject to the condition that

$$2\pi t_0^{-1} > C\left(1 + \frac{1}{\omega} |\operatorname{Re} z|\right).$$

Choose $0 < \varepsilon < 1$ so small that

$$(4.9) \quad 2\pi t_0^{-1} \geq C\left(1 + \left(\frac{1+\varepsilon}{\omega} + \varepsilon\right) |\operatorname{Re} z|\right).$$

Fix $0 < t < t_0$ arbitrary. By (4.6) there exists a sequence of complex numbers $(z_k(t))_{k \geq 1}$ such that

$$(4.10) \quad \lim_{k \rightarrow \infty} z_k(t) = z$$

with $\exp(tz_k(t)) \in \exp(tB)$ for all k . Most of the remaining argument is devoted to proving that $z_k(t) \in B$ for all sufficiently large k .

Choose $k_0(t)$ so large that

$$(4.11) \quad |z_k(t) - z| \leq \varepsilon |\operatorname{Re} z|$$

for all $k \geq k_0(t)$. Fix $k \geq k_0(t)$ and notice that, by (4.11) and the fact that $0 < \varepsilon < 1$,

$$(4.12) \quad \operatorname{Re} z_k(t) \geq 2 \operatorname{Re} z.$$

Choose integers $n_k(t) \geq 1$ and $N_k(t) \in \mathbb{Z}$ such that

$$(4.13) \quad z_k(t) = 2\pi i t^{-1} N_k(t) + \sum_{j=1}^{n_k(t)} \zeta_{j,k}(t)$$

with all $\zeta_{j,k}(t)$ in $\sigma(A)$. Note that for all j ,

$$(4.14) \quad \operatorname{Re} \zeta_{j,k}(t) \leq -\omega$$

and hence, by (4.13),

$$(4.15) \quad \operatorname{Re} z_k(t) \leq -n_k(t)\omega.$$

Also notice that from (4.12), (4.13), and (4.14),

$$(4.16) \quad \operatorname{Re} \zeta_{j,k}(t) \geq 2 \operatorname{Re} z.$$

From (4.11) and (4.15) we deduce that

$$n_k(t)\omega \leq |\operatorname{Re} z_k(t)| \leq (1 + \varepsilon) |\operatorname{Re} z|.$$

By (4.16) and the choice of C we have $|\operatorname{Im} \zeta_{j,k}(t)| \leq C$ and therefore, by (4.8), (4.11), (4.13), (4.16), and the fact that $C \geq 1$,

$$(4.17) \quad \begin{aligned} C &\geq |\operatorname{Im} z| \geq |\operatorname{Im} z_k| - \varepsilon C |\operatorname{Re} z| \\ &\geq 2\pi t^{-1} N_k(t) - C n_k(t) - \varepsilon C |\operatorname{Re} z| \\ &\geq 2\pi t^{-1} N_k(t) - (1 + \varepsilon) C |\operatorname{Re} z| / \omega - \varepsilon C |\operatorname{Re} z|. \end{aligned}$$

If $N_k(t)$ were nonzero, then $N_k(t) \geq 1$ and in view of $0 < t < t_0$ the right hand side would be strictly greater than

$$(4.18) \quad 2\pi t_0^{-1} - (1 + \varepsilon) C |\operatorname{Re} z| / \omega - \varepsilon C |\operatorname{Re} z| \geq C,$$

where the inequality follows from the choice of ε . By comparing (4.17) and (4.18) we see that we have arrived at a contradiction. Thus, $N_k(t) = 0$ and therefore, $z_k(t) = \sum_{j=1}^{n_k(t)} \zeta_{j,k}(t)$. It follows that $z_k(t) \in B$.

So far, $k \geq k_0(t)$ was fixed. By letting $k \rightarrow \infty$ and recalling (4.10) we obtain $z \in \overline{B}$. \square

If the eventual norm continuity assumption is strengthened to eventual compactness, there is no need to take the closure in (4.3). This is the content of the following semigroup analogue of Corollary 3.5:

Corollary 4.4. *Let $p \in (1, \infty)$. If S is strictly contractive and eventually compact, then P_p is eventually compact and*

$$\sigma(L_p) = \left\{ \sum_{j=1}^n k_j z_j : k_j \in \mathbb{N}, z_j \in \sigma(A); j = 1, \dots, n; n \geq 1 \right\}.$$

Proof. Let $S(t)$ be compact for $t > t_0$. Since $\mathcal{H}_n = \mathcal{H}_{p,n}$ with equivalent norms and since $T^{\otimes n}$ is compact whenever T is, the operators $P_{p,n}(t)$ are compact for $t > t_0$. The expansion (4.1) then shows that $P_p(t)$ is compact for $t > t_0$. Hence by the spectral mapping theorem for the point spectrum, $\sigma(L_p)$ consists of isolated eigenvalues and the result follows from Theorem 4.3. \square

5. THE L^p -SPECTRUM OF ORNSTEIN-UHLENBECK OPERATORS

Let E be a real Banach space, let A be infinitesimal generator of a strongly continuous semigroup $S = \{S(t)\}_{t \geq 0}$ on E , and let $Q \in \mathcal{L}(E^*, E)$ be a positive and symmetric operator. In this section we shall apply our abstract results to the Ornstein-Uhlenbeck operator L , given on a suitable core of cylindrical functions by

$$(5.1) \quad Lf(x) := \frac{1}{2} \text{Tr}(QD^2f(x)) + \langle Ax, Df \rangle \quad (x \in E)$$

where D denotes the Fréchet derivative. The operator L arises as the infinitesimal generator of the transition semigroup of the Markov process $\{U_x(t)\}_{t \geq 0}$ that solves the stochastic linear evolution equation

$$(5.2) \quad \begin{aligned} dU(t) &= AU(t) dt + dW_Q(t) & (t \geq 0) \\ U(0) &= x \end{aligned}$$

where W_Q is a cylindrical Q -Wiener process in E ; cf. [7, 10].

For $t > 0$ we define the positive symmetric operators $Q_t \in \mathcal{L}(E^*, E)$ by

$$Q_t x^* := \int_0^t S(s) Q S^*(s) x^* ds \quad (x^* \in E^*).$$

The right hand side integral is easily shown to exist as a Bochner integral in E . In order to give a rigorous description of the operator L , unless otherwise stated we shall assume in the remainder of this section that the following two hypotheses hold:

- (HQ $_{\infty}$) The weak operator limit $Q_{\infty} := \lim_{t \rightarrow \infty} Q_t$ exists in $\mathcal{L}(E^*, E)$;
- (H μ_{∞}) The operator Q_{∞} is the covariance of a centred Gaussian Radon measure μ_{∞} on E .

It will follow from Lemma 5.1 below that there is no loss of generality in assuming that μ_{∞} is nondegenerate.

Some comments are in order.

- (1) By Hypothesis (HQ $_{\infty}$), for all $x^*, y^* \in E^*$ we have

$$\langle Q_{\infty} x^*, y^* \rangle = \int_0^{\infty} \langle S(s) Q S^*(s) x^*, y^* \rangle ds,$$

the scalar integrals being defined in the improper sense. The positivity of Q together with a polarization argument imply that these integrals are actually absolutely convergent.

- (2) Hypothesis $(H\mu_\infty)$ and a standard tightness argument imply that each Q_t is the covariance operator of a centred Gaussian Radon measure μ_t , and we have $\lim_{t \rightarrow \infty} \mu_t = \mu_\infty$ weakly.
- (3) If E is separable, the word ‘Radon’ may be replaced by ‘Borel’.
- (4) If E is a Hilbert space and we identify E and E^* in the usual way, then Hypotheses (HQ_∞) and $(H\mu_\infty)$ hold if and only if each Q_t is of trace class and $\sup_{t > 0} \text{Tr } Q_t < \infty$. Furthermore if Hypothesis (HQ_∞) holds, then Hypothesis $(H\mu_\infty)$ holds if and only if Q_∞ is of trace class. In particular if $\dim E < \infty$, then Hypothesis (HQ_∞) implies $(H\mu_\infty)$.

As is shown in [7, 10], the existence of the measures μ_t is equivalent to the existence of a (necessarily unique) weak solution $\{U(t, x)\}_{t \geq 0}$ of (5.2). This solution is Gaussian; the random variable $U(t, x)$ has mean $S(t)x$ and covariance operator Q_t . The solution is also Markovian and its transition semigroup $P = \{P(t)\}_{t \geq 0}$ on $B_b(E)$ is given by

$$P(t)f(x) = \mathbb{E} f(U(t, x)) = \int_E f(S(t)x + y) d\mu_t(y) \quad (x \in E, f \in B_b(E)).$$

Here $B_b(E)$ denotes the space of bounded complex-valued Borel measurable functions on E . This semigroup leaves $C_b(E)$, the subspace of all continuous functions in $B_b(E)$, invariant. Although the restricted semigroup generally fails to be strongly continuous in the norm topology of $C_b(E)$, it is strongly continuous in the strict topology of $C_b(E)$. This is, by definition, the finest locally convex topology τ on $C_b(E)$ that agrees with the compact-open topology on bounded sets. As a result, the infinitesimal generator L of P is well defined as a linear operator on the domain

$$\mathcal{D}(L) = \left\{ f \in C_b(E) : \tau\text{-}\lim_{t \downarrow 0} \frac{1}{t}(P(t)f - f) \text{ exists in } C_b(E) \right\}.$$

On a suitable core of cylindrical functions, L is given by (5.1). The measure μ_∞ is *invariant* for L in the sense that for all $t \geq 0$ and $f \in B_b(E)$ we have

$$\int_E P(t)f(x) d\mu_\infty(x) = \int_E f(x) d\mu_\infty(x).$$

For more details we refer to the survey paper [14].

By standard arguments, the invariance of μ_∞ implies that P extends to a strongly continuous contraction semigroup P_p on $L^p(E, \mu_\infty)$ for all $p \in [1, \infty)$. The infinitesimal generator of P_p will be denoted by L_p . In order to establish the relationship between these semigroups and the ones studied in the previous section, we describe next how P_2 arises as a second quantized semigroup.

Let us denote the reproducing kernel Hilbert space associated with Q_∞ by H_∞ and the embedding $H_\infty \hookrightarrow E$ by i_∞ . The key fact is the following result, due to Chojnowska-Michalik and Goldys [9] under some additional assumptions; the present formulation was given in [21, Theorem 6.2].

Lemma 5.1. *Assume Hypothesis (HQ_∞) . The space H_∞ is invariant under the action of S , and the restriction of S to H_∞ , denoted by S_∞ , is a strongly continuous semigroup of contractions on H_∞ .*

By complexification, $S_{\infty, \mathbb{C}}$ is a strongly continuous semigroup of contractions on $H_{\infty, \mathbb{C}}$, and upon identifying $L^2(E, \mu_\infty)$ with $\Gamma^\otimes(H_{\infty, \mathbb{C}})$ as explained in the previous section we have the following representation of P_2 , again due to Chojnowska-Michalik and Goldys [9]; see also [21, Theorem 6.12]:

Proposition 5.2. *For all $t \geq 0$ we have $P_2(t) = \Gamma^{\otimes}(S_{\infty, \mathbb{C}}^*(t))$.*

Under this identification, the semigroup P_p agrees with the one introduced in the previous section. As an immediate consequence of Theorem 4.3, Corollary 4.4, and Proposition 5.2 we obtain:

Theorem 5.3. *If S_{∞} is strictly contractive and eventually norm continuous, then*

$$\sigma(L_p) = \overline{\left\{ \sum_{j=1}^n k_j z_j : k_j \in \mathbb{N}, z_j \in \sigma(A_{\infty}); j = 1, \dots, n; n \geq 1 \right\}}.$$

If in addition S_{∞} is compact, then

$$\sigma(L_p) = \left\{ \sum_{j=1}^n k_j z_j : k_j \in \mathbb{N}, z_j \in \sigma(A_{\infty}); j = 1, \dots, n; n \geq 1 \right\}.$$

Notice that $\sigma(L_p)$ depends on $\sigma(A_{\infty})$ rather than on $\sigma(A)$. This can be understood by observing that the definition of L_p depends not only on A , but also on Q . On a deeper level, the abstract results of the previous section show that Theorem 5.3 is in fact completely natural: Theorem 4.3 shows that it can be interpreted as saying that $\sigma(L_p)$ can be computed from the part of L_p in the first Wiener chaos. Of course, this limits that practical use of Theorem 5.3 to some extent, as in general it may be difficult to compute $\sigma(A_{\infty})$ from A and Q .

In the next two subsections we prove that the assumptions on S_{∞} are automatically satisfied in two important cases: the strong Feller case and the finite-dimensional case. In both cases we check the strict contractivity assumption by an appeal to the following result, due to Chojnowska-Michalik and Goldys [9]; cf. also [21, Theorem 6.3].

Lemma 5.4. *Assume Hypothesis (HQ $_{\infty}$) and fix $t > 0$. Then $\|S_{\infty}(t)\|_{\mathcal{L}(H_{\infty})} < 1$ if and only if $H_t = H_{\infty}$ with equivalent norms.*

Here H_t is the reproducing kernel Hilbert space associated with the positive symmetric operator Q_t introduced in the previous section.

The following example shows that a uniformly exponentially stable semigroup may fail to be strictly contractive even if $\dim E < \infty$, and that even if S_{∞} is strictly contractive it may happen that there exists no constant $a > 0$ such that $\|S_{\infty}(t)\|_{\mathcal{L}(H_{\infty})} \leq e^{-at}$ for all $t \geq 0$.

Example 5.5. For $\omega > 0$ we consider the semigroup $S^{(\omega)}$ on $E = \mathbb{R}^2$ defined by $S^{(\omega)}(t) = e^{-\omega t} \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix}$. This semigroup is uniformly exponentially stable, but for each $0 < \omega < 1$ we have $\|S^{(\omega)}(t)\| > 1$ for $t > 0$ small enough.

Let us now take $Q = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$. With this choice, the limit $Q_{\infty}^{(\omega)} = \lim_{t \rightarrow \infty} Q_t^{(\omega)}$ exists for every $\omega > 0$. Taking $\omega = 1$, by the computations in [14, Example 5.5] we have

$$\|S_{\infty}^{(1)}(t)\|_{\mathcal{L}(H_{\infty}^{(1)})} = e^{-t}(t + \sqrt{t^2 + 1}).$$

Thus, $S_{\infty}^{(1)}(t)$ is strictly contractive on $H_{\infty}^{(1)}$ but there exists no $a > 0$ such that $\|S_{\infty}^{(1)}(t)\|_{\mathcal{L}(H_{\infty}^{(1)})} \leq e^{-at}$ for all $t \geq 0$.

5.1. The strong Feller case. Throughout this subsection we assume the Hypotheses (HQ_∞) and $(\text{H}\mu_\infty)$ to hold. The transition semigroup P is said to be *strongly Feller* if $P(t)f \in C_b(E)$ for all $f \in B_b(E)$ and $t > 0$. We have the following reproducing kernel Hilbert space characterization of this property; see [10] and [21, Corollary 2.3].

Lemma 5.6. *The semigroup P is strongly Feller if and only if $S(t)E \subseteq H_t$ for all $t > 0$.*

The assumptions on S_∞ in Theorem 5.3 are satisfied in the strong Feller case:

Proposition 5.7. *If the transition semigroup P is strongly Feller, then S_∞ is compact and strictly contractive.*

Proof. By (2.4) we have a continuous inclusion $H_t \hookrightarrow H_\infty$; the inclusion mapping will be denoted by $i_{t,\infty}$. Denoting the inclusion mapping $H_t \hookrightarrow E$ by i_t , we have $i_t = i_\infty \circ i_{t,\infty}$. By Lemma 5.6 we have a factorization

$$(5.3) \quad S_\infty(t) = i_{t,\infty} \circ \Sigma(t) \circ i_\infty,$$

where $\Sigma(t)$ is the operator $S(t)$, viewed as an operator from E into H_t . Recalling from Section 2 that i_∞ is compact, it follows that $S_\infty(t)$ is compact for every $t > 0$.

By Lemma 5.4 it remains to prove that for all $t > 0$ we have $H_t = H_\infty$ with equivalent norms. We have already seen that $H_t \hookrightarrow H_\infty$ with continuous inclusion. To obtain the reverse inclusion we apply i_∞ on both sides of (5.3) to obtain the identity

$$S(t) \circ i_\infty = i_\infty \circ S_\infty(t) = i_t \circ \Sigma(t) \circ i_\infty.$$

Together with the identity $Q_\infty = Q_t + S(t)Q_\infty S^*(t)$, which follows directly from the definitions of Q_t and Q_∞ , for $x^* \in E^*$ we obtain

$$\begin{aligned} \langle Q_\infty x^*, x^* \rangle &= \langle Q_t x^*, x^* \rangle + \langle Q_\infty S^*(t)x^*, S^*(t)x^* \rangle \\ &= \langle Q_t x^*, x^* \rangle + [i_\infty^* S^*(t)x^*, i_\infty^* S^*(t)x^*]_{H_\infty} \\ &= \langle Q_t x^*, x^* \rangle + [i_\infty^* \Sigma^*(t)i_t^* x^*, i_\infty^* \Sigma^*(t)i_t^* x^*]_{H_\infty} \\ &= \langle Q_t x^*, x^* \rangle + \langle Q_\infty \Sigma^*(t)i_t^* x^*, \Sigma^*(t)i_t^* x^* \rangle \\ &\leq \langle Q_t x^*, x^* \rangle + \|Q_\infty\|_{\mathcal{L}(E^*, E)} \|\Sigma(t)\|_{\mathcal{L}(E, H_t)}^2 \|i_t^* x^*\|_{H_t}^2 \\ &= (1 + \|Q_\infty\|_{\mathcal{L}(E^*, E)} \|\Sigma(t)\|_{\mathcal{L}(E, H_t)}^2) \langle Q_t x^*, x^* \rangle. \end{aligned}$$

The desired inclusion now follows from (2.4). \square

Summarizing our discussion we have proved:

Theorem 5.8. *If the transition semigroup generated by L is strongly Feller, then*

$$\sigma(L_p) = \left\{ \sum_{j=1}^n k_j z_j : k_j \in \mathbb{N}, z_j \in \sigma(A_\infty); j = 1, \dots, n; n \geq 1 \right\}.$$

5.2. The finite-dimensional case. We will show next that the assumptions on S_∞ in Theorem 5.3 are also satisfied if $\dim E < \infty$. Since in finite dimensions every strongly continuous semigroup is compact, we only have to check the strict contractivity assumption.

In the following result we do not *a priori* assume Hypothesis (HQ_∞) . We identify E and its dual in the natural way.

Proposition 5.9. *Let $\dim E < \infty$. The following assertions are equivalent:*

- (1) $Q_\infty := \lim_{t \rightarrow \infty} Q_t$ exists and Q_∞ is invertible;
(2) Q_t is invertible for all $t > 0$ and S is uniformly exponentially stable.

In this situation we have $H_t = H_\infty = E$ with equivalent norms and S_∞ is a strict contraction semigroup.

Proof. (1) \Rightarrow (2): From $\text{rank } Q_\infty = n$ and $\lim_{t \rightarrow \infty} Q_t = Q_\infty$ we have $\text{rank } Q_t = n$ for large enough t . For these t we have $H_t = \text{range } Q_t = E$. On the other hand, since the subspaces H_t increase with t and since their dimensions can make only finitely many jumps, there is a time $t_0 > 0$ such that $H_t = H_{t_0}$ for all $0 < t \leq t_0$. It then follows from [21, Theorem 1.4] that $S(s)$ maps $H_{t_0} = \text{range } Q_{t_0}$ into itself for all $s \geq 0$. The identity

$$Q_{kt_0} = Q_{t_0} + \cdots + S((k-1)t_0)Q_{t_0}S^*((k-1)t_0)$$

then implies that

$$H_{kt_0} = \text{range } Q_{kt_0} \subseteq \text{range } Q_{t_0} = H_{t_0} = H_t$$

for all $k \geq 1$. But by the observations already made, for k large enough we have $H_{kt_0} = E$ and therefore $H_t = E$ for all $0 < t \leq t_0$. But then we have $H_t = E$ for all $t > 0$. This means that Q_t is invertible for all $t > 0$.

The above arguments show that for all $t > 0$, $H_t = H_\infty = E$ with equivalent norms. By Lemma 5.4, the first of these identities implies that S_∞ is a strict contraction semigroup. The second of these identities then implies that E can be renormed in such a way that S is a strict contraction group. In particular, S is uniformly exponentially stable.

(2) \Rightarrow (1): The existence of the limit defining Q_∞ is obvious from the uniform exponential stability of S . The invertibility of Q_∞ follows the inclusion $H_t \subseteq H_\infty$: the invertibility of Q_t means that $H_t = E$ and therefore we have $H_\infty = E$ as well. \square

We cannot resist to present a direct proof of the strict contractivity of S_∞ which is based on a compactness argument and elementary spectral theory.

Fix $t > 0$. We claim that the operator $S_{\infty, \mathbb{C}}^*(t)$ cannot have an eigenvalue $|z| = 1$. Suppose the contrary and choose an eigenvector $h_1 + ih_2 \in H_{\infty, \mathbb{C}}$ with $h_1, h_2 \in H_\infty$ and $\|h_1 + ih_2\|_{H_{\infty, \mathbb{C}}} = 1$. Then for all $n \geq 1$,

$$S_{\infty, \mathbb{C}}^*(nt)(h_1 + ih_2) = z^n(h_1 + ih_2).$$

For at least one $j \in \{1, 2\}$ we have a sequence $n_k \rightarrow \infty$ such that

$$\|S_{\infty}^*(n_k t)h_j\|_{H_\infty}^2 \geq \frac{1}{2}$$

for all k . Since H_∞ is finite-dimensional and the range of i_∞^* is dense in H_∞ , i_∞^* is a surjection and we can find $x_j^* \in E^*$ such that $i_\infty^* x_j^* = h_j$. Then,

$$\begin{aligned} \frac{1}{2} &\leq \|S_{\infty}^*(n_k t)h_j\|_{H_\infty}^2 = \|S_{\infty}^*(n_k t)i_\infty^* x_j^*\|_{H_\infty}^2 = \|i_\infty^* S^*(n_k t)x_j^*\|_{H_\infty}^2 \\ &= \int_{n_k t}^{\infty} \langle S(s)Q S^*(s)x_j^*, x_j^* \rangle ds. \end{aligned}$$

By letting $k \rightarrow \infty$ we obtain a contradiction, as the right hand side will tend to 0.

Thus we have proved that $r(S_{\infty, \mathbb{C}}(t)) = r(S_{\infty, \mathbb{C}}^*(t)) < 1$. By Gelfand's formula for the spectral radius this implies that $\|S_{\infty, \mathbb{C}}(nt)\|_{\mathcal{L}(H_{\infty, \mathbb{C}})} < 1$ for sufficiently large n , and therefore $S_{\infty, \mathbb{C}}$ is uniformly exponentially stable. Then S_∞ is uniformly exponentially stable as well.

Let us now assume, for a contradiction, that $\|S_\infty(t)\|_{\mathcal{L}(H_\infty)} = 1$. By a compactness argument, we find an element $h \in H_\infty$ of norm one such that $\|S_\infty(t)h\|_{H_\infty} = 1$. Since S_∞ is a contraction semigroup, this implies that $\|S_\infty(s)h\|_{H_\infty} = 1$ for all $s \in [0, t]$. Differentiating the function $s \mapsto \|S_\infty(s)h\|_{H_\infty}^2 = [S_\infty(s)h, S_\infty(s)h]_{H_\infty}$ repeatedly with respect to s and evaluating at $s = 0$ gives $[A_\infty^n h, h]_{H_\infty} = 0$ for all $n \geq 1$. Hence, for any $r \geq 0$,

$$[S_\infty(r)h, h]_{H_\infty} = \sum_{n \geq 0} \frac{r^n}{n!} [A_\infty^n h, h]_{H_\infty} = [h, h]_{H_\infty} = 1.$$

But this contradicts the uniform exponential stability of S_∞ .

In the results so far we could assume without loss of generality that μ_∞ is nondegenerate, but this was nowhere essential. In our final result, the nondegeneracy is crucial:

Theorem 5.10. *If $\dim E < \infty$ and μ_∞ is nondegenerate, then for all $p \in (1, \infty)$ we have*

$$\sigma(L_p) = \left\{ \sum_{j=1}^n k_j z_j : k_j \in \mathbb{N}, z_j \in \sigma(A); j = 1, \dots, n; n \geq 1 \right\}.$$

Proof. Since $\dim E < \infty$, the nondegeneracy of μ_∞ implies the invertibility of Q_∞ . Consequently we have $H_\infty = E$ with equivalent norms, and therefore $\sigma(A_\infty) = \sigma(A)$. The result now follows from the second part of Theorem 5.3. \square

In [19], Theorem 5.10 was proved under the assumptions that $\dim E < \infty$, Q_t is invertible for all $t > 0$, and S is uniformly exponentially stable. By Proposition 5.9 and the fact that in finite dimensions every positive symmetric operator is a Gaussian covariance, these assumptions are equivalent to the ones of Theorem 5.10, viz. the existence of a nondegenerate invariant measure.

It was observed in [19] that all generalized eigenvectors of L_p are polynomials. This fact follows effortlessly from our approach. First, by Theorem 5.3 and compactness, every $z \in \sigma(L_p)$ is an eigenvalue of finite multiplicity. If f is a generalized eigenvector, then for all n sufficiently large, $\sum_{j=0}^n I_{p,n} f$ is nonzero and therefore a generalized eigenvector as well. But since the generalized eigenspace of z is finite-dimensional, at most finitely many $I_{p,n} f$ are nonzero. Hence, $f = \sum_{k=1}^m I_{p,n_k} f$ with each $I_{p,n_k} f \in \mathcal{H}_{p,n_k}$. But each \mathcal{H}_{p,n_k} is the linear span of a finite set of polynomials, and therefore f is a polynomial.

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