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Kyoto University
Wick Product of White Noise Operators and Its Application to Quantum Stochastic Differential Equations

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Introduction

After the famous paper by Hudson–Parthasarathy [11] quantum stochastic processes on the (Boson) Fock space $\Gamma(L^2(\mathbb{R}))$ have been developed considerably by many authors, see the excellent books by Meyer [14] and by Parthasarathy [23] and references cited therein. In those works the annihilation process $\{A_t\}$, the creation process $\{A_t^*\}$ and the number process $\{\Lambda_t\}$ are considered as primary quantum noises and the bulk is devoted to establishing a quantum analogue of Itô theory, where the role of infinitesimal increment of the Brownian motion $dB_t$ in the classical Itô theory is played by $dA_t$, $dA_t^*$ and $d\Lambda_t$. Thus quantum stochastic differential equations to be discussed are typically of the form

$$dU = (L_1dA + L_2dA + L_3dA^* + L_4dt)U, \quad U(0) = I. \quad (0.1)$$

Here, at the request of physical applications an initial Hilbert space or a system Hilbert space $\mathcal{H}$ being taken into account, $L_i$ are operators acting on $\mathcal{H}$ and the solution $U_t$ will be an operator process acting on $\mathcal{H} \otimes \Gamma(L^2(\mathbb{R}))$.

On the other hand, in view of the white noise approach to classical stochastic analysis (see, e.g., Kuo [13]), one expects that white noise distribution theory (WNDT) leads to a breakthrough in quantum stochastic analysis. In fact, during recent years white noise approach to quantum stochastic processes has initiated by a series of papers [18], [19], [20], [21], [22], etc., see also [9], [10]. The essence of this approach lies in the fact that every quantum stochastic process is expressible in terms of two quantum noises $\{a_t\}$ and $\{a_t^*\}$, which are time derivatives of the annihilation and the creation processes, that is, $dA_t = a_t dt$ and $dA_t^* = a_t^* dt$. From that viewpoint (0.1) is reduced to

$$\frac{dU}{dt} = (L_1a_t^*a_t + L_2a_t + L_3a_t^* + L_4)U, \quad (0.2)$$

or in the normal form:

$$\frac{dU}{dt} = L_1a_t^*Ua_t + L_2UA_t + L_3a_t^*U + L_4U. \quad (0.3)$$
Moreover, during the lectures of Accardi [2] a new type of a quantum stochastic differential equation such as
\[
\frac{dU}{dt} = (M_1a_t^2 + M_2a_t^2)U
\]
comes within our scope (though the above equation is understood just formally at the moment). Note that an equation as in (0.4) is highly singular from the usual aspect.

The main purpose of this paper is to give a first step toward a new theory of quantum stochastic differential equations on the basis of WNDT. We introduce the Wick product (or normal product) of operators by means of the characterization theorem of operator symbols. We then discuss existence and uniqueness of a solution of a certain class of quantum stochastic differential equations which possess fairly singular coefficients. It turns out that the refreshed WNDT due to Kuo [13], where the Hida–Kubo–Takenaka space is replaced with the Kondratiev–Streit space, is more suitable for our purpose. This generalization, however, causes no new difficulty since most basic results obtained so far for the Hida–Kubo–Takenaka space [15] admit straightforward generalizations to the Kondratiev–Streit space. We hope that our theory is also applied to some problems in quantum dissipation discussed by Accardi [1], [2], Arimitsu [4], Gardiner [8], Saito–Arimitsu [24], etc.

1 WNDT – White noise distribution theory

Let $H = L^2(\mathbb{R}, dt; \mathbb{R})$ be the real Hilbert space of $\mathbb{R}$-valued $L^2$-functions on $\mathbb{R}$. The norm and the inner product are denoted by $|\cdot|_0$ and $\langle \cdot , \cdot \rangle$, respectively. Then consider the real Gelfand triple
\[
E = S(\mathbb{R}) \subset H = L^2(\mathbb{R}, dt; \mathbb{R}) \subset E^* = S'(\mathbb{R}).
\]
Being a natural extension of the inner product of $H$, the canonical bilinear form on $E^* \times E$ is denoted by the same symbol $\langle \cdot , \cdot \rangle$. Let $\mu$ be the standard Gaussian measure on $E^* \times L^2(E^*, \mu)$ the Hilbert space of $\mathbb{C}$-valued $L^2$-functions on $E^*$. The celebrated Wiener–Itô–Segal theorem says that $L^2(E^*, \mu)$ is unitarily isomorphic to the Boson Fock space $\Gamma(H_C)$, where $H_C$ is the complexification of $H$. The isomorphism is a unique linear extension of the following correspondence between exponential functions and exponential vectors:
\[
\phi_\xi(x) = e^{\langle x, \xi \rangle - \langle \xi, \xi \rangle/2} \leftrightarrow \left(1, \xi, \frac{\xi^\otimes 2}{2!}, \cdots, \frac{\xi^\otimes n}{n!}, \cdots \right),
\]
where $\xi$ runs over $E_C$. If $\phi \in L^2(E^*, \mu)$ and $(f_n)_{n=0}^\infty \in \Gamma(H_C)$ are related by the Wiener–Itô–Segal isomorphism, we write
\[
\phi \sim (f_n)
\]
for simplicity. It is then noted that
\[
\| \phi \|^2_0 = \sum_{n=0}^{\infty} n! |f_n|^2_0,
\]
where $\| \phi \|_0$ is the $L^2$-norm of $\phi \in L^2(E^*, \mu)$.

In order to introduce white noise distributions we need a particular family of seminorms defining the topology of $E = S(\mathbb{R})$. By means of the differential operator $A = 1 + t^2 - d^2/2t^2$
we introduce a sequence of norms in $H_{\mathbb{C}}$ in such a way that $|\xi|_{p} = |A^{p}\xi|_{0}$. Let $E_{p}$ be the Hilbert space obtained by completing $E$ with respect to the norm $| \cdot |_{p}$. Then it is known that

$$E \cong \text{proj lim}_{p \to \infty} E_{p}, \quad E^{*} \cong \text{ind lim}_{p \to \infty} E_{-p},$$

where the dual space carries the strong dual topology. The norms $| \cdot |_{p}$ are naturally extended to the tensor products $E^{\otimes n}$ and their complexification $E_{\mathbb{C}}^{\otimes n}$. The canonical bilinear form $\langle \cdot, \cdot \rangle$ is also extended to a complex bilinear form on $(E_{\mathbb{C}}^{\otimes n})^{*} \times E_{\mathbb{C}}^{\otimes n}$.

Throughout the paper let $\beta$ be a fixed number with $0 \leq \beta < 1$. For $\phi \in L^{2}(E^{*}, \mu)$ we introduce a new norm

$$\| \phi \|_{p, \beta}^{2} = \sum_{n=0}^{\infty} (n!)^{1+\beta}|f_{n}|_{p}^{2}, \quad \phi \sim (f_{n}). \quad (1.2)$$

Then $(E_{p})_{\beta} = \{ \phi ; |\phi|_{p, \beta} < \infty \}$, $p \geq 0$, becomes a Hilbert space and

$$(E)_{\beta} = \text{proj lim}_{p \to \infty} (E_{p})_{\beta}$$

a countable Hilbert nuclear space. Similarly,

$$\| \phi \|_{-p, -\beta}^{2} = \sum_{n=0}^{\infty} (n!)^{1-\beta}|f_{n}|_{-p}^{2}, \quad \phi \sim (f_{n}), \quad (1.3)$$

defines a Hilbertian norm on $L^{2}(E^{*}, \mu)$ and we denote by $(E_{-p})_{-\beta}$ the completion. Then the dual space (with the strong dual topology as usual) of $(E)_{\beta}$ is obtained as

$$(E)_{\beta}^{*} \cong \text{ind lim}_{p \to \infty} (E_{-p})_{-\beta} = \bigcup_{p \geq 0} (E_{-p})_{-\beta}.$$ 

The resultant Gelfand triple

$$(E)_{\beta} \subset L^{2}(E^{*}, \mu) \subset (E)_{\beta}^{*} \quad (1.4)$$

is called the Kondratiev–Streit space. The canonical bilinear form on $(E)_{\beta}^{*} \times (E)_{\beta}$ will be denoted by $\langle \langle \cdot, \cdot \rangle \rangle$. Then

$$\langle \langle \phi, \phi \rangle \rangle = \sum_{n=0}^{\infty} n! \langle F_{n}, f_{n} \rangle, \quad \Phi \sim (F_{n}) \in (E)_{\beta}^{*}, \quad \phi \sim (f_{n}) \in (E)_{\beta}. \quad (1.5)$$

We note that (1.1), (1.2), (1.3) and (1.5) are all compatible each other. The standard Hida–Kubo–Takenaka space is the case of $\beta = 0$ in (1.4). Moreover, there holds a natural inclusion relation:

$$(E)_{\beta} \subset (E)_{0} = (E) \subset L^{2}(E^{*}, \mu) \subset (E)^{*} = (E)_{0}^{*} \subset (E)_{\beta}^{*}.$$ 

2 Operator symbols

The essence of white noise approach to Fock space operators consists of effective use of pointwisely defined annihilation and creation operators, integral kernel operators, Fock expansion and operator symbols. Observing Kuo’s discussion [13] carefully, we are convinced

We first recall pointwisely defined annihilation and creation operators. For any \( t \in \mathbb{R} \) there exists an operator \( a_t \in \mathcal{L}((E)_\beta, (E)_\beta) \) uniquely determined by
\[
a_t \phi \xi = \xi(t) \phi \xi, \quad \xi \in E_C.
\]
The above \( a_t \) is called the annihilation operator at a point \( t \) and its adjoint \( a_t^* \in \mathcal{L}((E)_\beta^*, (E)_\beta^*) \) the creation operator at a point \( t \). It is easily seen (cf. [15, §4.1]) that
\[
\|a_t \phi\|_{p,\beta} \leq \left(\frac{(1-\beta)\rho^{-\frac{1-\beta}{2}}}{-2qe \log \rho}\right)^{(1-\beta)/2} \| \delta_t \|_{-p+q,q,\beta} \| \phi \|_{p+q,\beta}, \quad \phi \in (E)_\beta, \quad p \in \mathbb{R}, \quad q \geq 0,
\]
where \( \rho = \|A^{-1}\|_{op} = 1/2 \).

Recall next operator symbols. Since the exponential vectors \( \{ \phi_\xi; \xi \in E_C \} \) span a dense subspace of \( (E)_\beta \), every continuous operator \( \Xi \in \mathcal{L}((E)_\beta, (E)_\beta^*) \) is determined uniquely by its symbol
\[
\hat{\Xi}(\xi, \eta) = \langle \langle \Xi \phi_\xi, \phi_\eta \rangle \rangle, \quad \xi, \eta \in E_C.
\]
For instance, for an integral kernel operator \( \Xi_{l,m}(\kappa) \), \( \kappa \in (E_{\mathbb{C}}^{\otimes(l+m)})^* \), we have
\[
\Xi_{l,m}(\kappa)^*(\xi, \eta) = \langle \kappa, \eta^{\otimes l} \otimes \xi^{\otimes m} \rangle e^{\langle \epsilon, \eta \rangle}, \quad \xi, \eta \in E_C,
\]
where an integral kernel operator \( \Xi_{l,m}(\kappa) \) admits a formal integral expression:
\[
\Xi_{l,m}(\kappa) = \int_{\mathbb{R}^{l+m}} \kappa(s_1, \cdots, s_l, t_1, \cdots, t_m)a_{s_1}^* \cdots a_{s_l}^* a_{t_1} \cdots a_{t_m} ds_1 \cdots ds_l dt_1 \cdots dt_m,
\]
for a rigorous definition see [15]. As a result, \( \Xi_{l,m}(\kappa) \) is uniquely determined by (2.2).

We next need a stratification of the space \( \mathcal{L}((E)_\beta, (E)_\beta^*) \). By the kernel theorem there is a canonical isomorphism:
\[
\mathcal{L}((E)_\beta, (E)_\beta^*) \cong ((E)_\beta \otimes (E)_\beta)^* = \bigcup_{p \geq 0}(E-p)_{-\beta} \otimes (E-p)_{-\beta}.
\]
Let \( \mathcal{L}_p((E)_\beta, (E)_\beta^*) \) denote the space of all operators \( \Xi \in \mathcal{L}((E)_\beta, (E)_\beta^*) \) which correspond to elements (denoted by the same symbols) in \( (E-p)_{-\beta} \otimes (E-p)_{-\beta} \). The norm is denoted by
\[
\| \langle \langle \Xi \phi, \psi \rangle \rangle \| = \| \langle \langle \Xi, \phi \otimes \psi \rangle \rangle \| \leq \| \Xi \|_{-p,-\beta} \| \phi \|_{p,\beta} \| \psi \|_{p,\beta}, \quad \phi, \psi \in (E)_\beta.
\]
In particular, in view of
\[
\| \phi_\xi \|_{p,\beta} \leq 2^{\beta/2} \exp \left\{ (1-\beta)2^{\frac{2\beta-1}{1-\beta}} \| \xi \|_{p}^{\frac{2}{1-\beta}} \right\}, \quad \xi \in E_C,
\]
which is found in [13, §5.2], we have
\[
\| \langle \langle \Xi \phi_\xi, \phi_\eta \rangle \rangle \| \leq 2^{\beta} \| \Xi \|_{-p,-\beta} \exp \left\{ (1-\beta)2^{\frac{2\beta-1}{1-\beta}} \left( \| \xi \|_{p}^{\frac{2}{1-\beta}} + \| \eta \|_{p}^{\frac{2}{1-\beta}} \right) \right\},
\]
or equivalently,
\[
\| \hat{\Xi}(\xi, \eta) \| \leq 2^{\beta} \| \Xi \|_{-p,-\beta} \exp \left\{ (1-\beta)2^{\frac{2\beta-1}{1-\beta}} \left( \| \xi \|_{p}^{\frac{2}{1-\beta}} + \| \eta \|_{p}^{\frac{2}{1-\beta}} \right) \right\}.
\]
Theorem 2.1 For a \(C\)-valued function \(\Theta : E_C \times E_C \to \mathbb{C}\) to be the symbol of an operator \(\Xi \in \mathcal{L}(E)_{\beta}, (E)_{\beta}^{*}\) if and only if

1. (O1) for fixed \(\xi, \xi_1, \eta, \eta_1 \in E_C\) the complex function \((z, w) \mapsto \Theta(z\xi + \xi_1, w\eta + \eta_1)\) is entire holomorphic on \(\mathbb{C} \times \mathbb{C}\);
2. (O2) there exist constant numbers \(C \geq 0, K \geq 0, p \geq 0\) such that

\[
|\Theta(\xi, \eta)| \leq C \exp K \left( |\xi|^{\frac{2}{p^{1-\beta}}} + |\eta|^{\frac{2}{p^{1-\beta}}} \right), \quad \xi, \eta \in E_C.
\]

The proof given in [15, §4.4] for the case of \(\beta = 0\) is adjusted to the general case of \(0 \leq \beta < 1\), see [13]. Note also that condition (O2) follows from (2.4).

Theorem 2.2 Let \(T\) be a locally compact space satisfying the first axiom of countability and let \(t_0 \in T\) be a fixed point. Then for the map \(t \mapsto \Xi_t \in \mathcal{L}(E)_{\beta}, (E)_{\beta}^{*}\), \(t \in T\), the following three conditions are equivalent:

1. (i) \(t \mapsto \Xi_t\) is continuous at \(t = t_0\);
2. (ii) there exist \(p \geq 0\) and an open neighborhood \(U\) of \(t_0\) such that

\[
\{\Xi_t; t \in U\} \subseteq \mathcal{L}_p((E)_{\beta}, (E)_{p}^{*}) \quad \text{and} \quad \lim_{t \to t_0} \|\Xi_t - \Xi_{t_0}\|_{-p, -\beta} = 0.
\]
3. (iii) there exist \(C \geq 0, K \geq 0, p \geq 0\) and an open neighborhood \(U\) of \(t_0\) such that

\[
|\tilde{\Xi}_t(\xi, \eta)| \leq C \exp K \left( |\xi|^{\frac{2}{p^{1-\beta}}} + |\eta|^{\frac{2}{p^{1-\beta}}} \right), \quad \xi, \eta \in E_C, \quad t \in U,
\]

(2.5)

and

\[
\lim_{t \to t_0} \tilde{\Xi}_t(\xi, \eta) = \tilde{\Xi}_{t_0}(\xi, \eta), \quad \xi, \eta \in E_C.
\]

Proof. (i) \(\iff\) (ii) follows from the general result in Appendix.

(ii) \(\Rightarrow\) (iii) In view of (2.4) we have

\[
|\tilde{\Xi}_t(\xi, \eta) - \tilde{\Xi}_{t_0}(\xi, \eta)| \leq 2^\beta \|\Xi_t - \Xi_{t_0}\|_{-p, -\beta} \exp \left\{ (1 - \beta)^{2\frac{\beta-1}{1-\beta}} \left( |\xi|^{\frac{2}{p^{1-\beta}}} + |\eta|^{\frac{2}{p^{1-\beta}}} \right) \right\},
\]

from which the assertion is clear.

(iii) \(\Rightarrow\) (i) By a similar argument as in [15, §4.4] there exist \(q \geq 0\) and \(M = M(K, p, q) \geq 0\) such that

\[
\|\Xi_t\phi\|_{-(p+q+1), -\beta} \leq CM \|\phi\|_{p+q+1, \beta}, \quad \phi \in (E)_{\beta}, \quad t \in U,
\]

and hence

\[
\|\Xi_t\|_{-(p'+q+2), -\beta} \leq CM \| \Gamma(A)^{-1} \|_H^2, \quad t \in U.
\]

By assumption

\[
\langle \Xi_t - \Xi_{t_0}, \phi_\xi \otimes \phi_\eta \rangle = \langle (\Xi_t - \Xi_{t_0})\phi_\xi, \phi_\eta \rangle \to 0, \quad t \to t_0.
\]
Since the exponential vectors span a dense subspace of \((E)_\beta\), for any \(\omega \in (E)_\beta \otimes (E)_\beta\) and \(\epsilon > 0\) there exists a linear combination of exponential vectors \(\omega' = \sum_i \phi_{\xi_i} \otimes \phi_{\eta_i}\) such that \(\|\omega - \omega'\|_{p+q+2,\beta} < \epsilon\). By the triangle inequality

\[
|\langle \Xi_t - \Xi_{t_0}, \omega \rangle| \leq |\langle \Xi_t - \Xi_{t_0}, \omega - \omega' \rangle| + |\langle \Xi_{t_0}, \omega' \rangle|
\]

\[
\leq \|\Xi_t - \Xi_{t_0}\|_{-(p+q+2),-\beta} \|\omega - \omega'\|_{p+q+2,\beta} + \sum_i |\langle \Xi_t - \Xi_{t_0}, \phi_{\xi_i} \otimes \phi_{\eta_i}\rangle|
\]

\[
\rightarrow 2\epsilon CM\|\Gamma(A)^{-1}\|_H^2, \quad t \rightarrow t_0.
\]

Therefore \(\Xi_t\) converges to \(\Xi_{t_0}\) as \(t \rightarrow t_0\) with respect to the weak topology of \(((E)_\beta \otimes (E)_\beta)^*\), and hence with respect to the strong topology due to the first countability of \(T\). Since \(((E)_\beta \otimes (E)_\beta)^* \cong \mathcal{L}((E)_\beta, (E)^*_\beta)\) with respect to the strong topology, it follows that \(t \mapsto \Xi_t \in \mathcal{L}((E)_\beta, (E)^*_\beta)\) is continuous at \(t = t_0\).

**Theorem 2.3** Let \(\Theta_n\) be a sequence of \(C\)-valued functions defined on \(E_C \times E_C\) satisfying the following two conditions:

(i) for fixed \(\xi, \xi_1, \eta, \eta_1 \in E_C\) the complex function \((z, w) \mapsto \Theta_n(z\xi + \xi_1, w\eta + \eta_1)\) is entire holomorphic on \(\mathbb{C} \times \mathbb{C}\);

(ii) there exist \(C \geq 0, K \geq 0\) and \(p \geq 0\) such that

\[
|\Theta_n(\xi, \eta)| \leq C \exp K \left(||\xi||^\frac{2}{p} + ||\eta||^\frac{2}{p}\right), \quad \xi, \eta \in E_C, \quad n = 1, 2, \ldots (2.6)
\]

If for any \(\xi, \eta \in E_C\) the limit

\[
\Theta(\xi, \eta) \equiv \lim_{n \rightarrow \infty} \Theta_n(\xi, \eta)
\]

exists, then there exists \(\Xi \in \mathcal{L}((E)_\beta, (E)^*_\beta)\) such that \(\hat{\Xi} = \Theta\). In that case, denoting by \(\Xi_n \in \mathcal{L}((E)_\beta, (E)^*_\beta)\) an operator of which symbol is \(\Theta_n\), the sequence \(\Xi_n\) converges to \(\Xi\) in \(\mathcal{L}((E)_\beta, (E)^*_\beta)\).

**Proof.** Let \(\xi, \xi_1, \eta \in E_C\) be fixed. For simplicity we put

\[
g_n(z) = \Theta_n(z\xi + \xi_1, \eta), \quad g(z) = \Theta(z\xi + \xi_1, \eta), \quad z \in \mathbb{C}.
\]

We shall prove that \(g(z)\) is holomorphic on \(\mathbb{C}\). Suppose that \(\gamma\) is a smooth closed curve in \(\mathbb{C}\). Since \(g_n(z)\) is holomorphic by (i),

\[
\int_\gamma g_n(z)dz = 0.
\]

On the other hand, since \(\gamma\) is a compact set, by assumption (ii) there exists some \(M > 0\) such that

\[
|g_n(z)| \leq C \exp \left(||z\xi + \xi_1||^\frac{2}{p} + ||\eta||^\frac{2}{p}\right) \leq M, \quad z \in \gamma, \quad n = 1, 2, \ldots
\]
It then follows from the bounded convergence theorem that
\[ 0 = \lim_{n \to \infty} \int_{\gamma} g_n(z) \, dz = \int_{\gamma} g(z) \, dz. \]

Therefore \( g(z) \) is holomorphic by Morera's theorem. It is then clear that \( \Theta \) satisfies the same conditions (i) and (ii), and therefore by Theorem 2.1 there exists \( \Xi \in \mathcal{L}(\beta, (E)^{\star}) \) such that \( \hat{\Xi} = \Theta \). Thus condition (iii) in Theorem 2.2 is satisfied, and consequently, \( \Xi_n \) converges in \( \Xi \) in \( \mathcal{L}((E)_{\beta}, (E)^{*}_{\beta}) \).

\textbf{Remark} For an operator \( \Xi \in \mathcal{L}((E)_{\beta}, (E)^{*}_{\beta}) \) the function
\[ \hat{\Xi}(\xi, \eta) = \langle \langle \Xi \phi_{\xi}, \phi_{\eta} \rangle \rangle e^{-\langle \xi, \eta \rangle}, \quad \xi, \eta \in EC, \]
is called the Wick symbol, see [5], [6]. The symbol and Wick symbol are related in an obvious manner:
\[ \hat{\Xi}(\xi, \eta) = \hat{\Xi}(\xi, \eta) e^{-\langle \xi, \eta \rangle}. \]

It is then easy to see that the above mentioned statements are also valid when the "symbol" is replaced with "Wick symbol."

3 Wick product of operators

We start with the following

\textbf{Lemma 3.1} For two operators \( \Xi_1, \Xi_2 \in \mathcal{L}((E)_{\beta}, (E)^{*}_{\beta}) \) there exists \( \Xi \in \mathcal{L}((E)_{\beta}, (E)^{*}_{\beta}) \) such that
\[ \hat{\Xi}(\xi, \eta) = \hat{\Xi}_1(\xi, \eta) \hat{\Xi}_2(\xi, \eta) e^{-\langle \xi, \eta \rangle}, \quad \xi, \eta \in EC, \quad (3.1) \]

\textbf{PROOF.} We apply Theorem 2.1. For simplicity we put
\[ \Theta(\xi, \eta) = \hat{\Xi}_1(\xi, \eta) \hat{\Xi}_2(\xi, \eta) e^{-\langle \xi, \eta \rangle}, \quad \xi, \eta \in EC. \]

Obviously, condition (O1) in Theorem 2.1 is fulfilled. By assumption, we have
\[ |\hat{\Xi}_i(\xi, \eta)| \leq 2^\beta \| \Xi_i \|_{p, -\beta} \exp \left\{ (1 - \beta)2^{\frac{2\beta}{1 - \beta}} \left( |\xi|^{\frac{2}{p^{1 - \beta}}} + |\eta|^{\frac{2}{p^{1 - \beta}}} \right) \right\}, \quad i = 1, 2, \]
for some \( p \geq 0 \), see (2.4). On the other hand, in view of an obvious inequality \( a^2 \leq 1 + a^{2/(1 - \beta)} \) we have
\[ |e^{-\langle \xi, \eta \rangle}| \leq \exp \frac{\rho_{2^p}}{2} \left( |\xi|_p^2 + |\eta|_p^2 \right) \leq e^{\rho_{2^p}} \exp \frac{\rho_{2^p}}{2} \left( |\xi|_p^{\frac{2}{p^{1 - \beta}}} + |\eta|_p^{\frac{2}{p^{1 - \beta}}} \right). \]

Then,
\[ |\Theta(\xi, \eta)| \leq 2^{2\beta} \| \Xi_1 \|_{p, -\beta} \| \Xi_2 \|_{p, -\beta} \exp \left\{ 2(1 - \beta)2^{\frac{2\beta}{1 - \beta}} \left( |\xi|_p^{\frac{2}{p^{1 - \beta}}} + |\eta|_p^{\frac{2}{p^{1 - \beta}}} \right) \right\} \times e^{\rho_{2^p}} \exp \frac{\rho_{2^p}}{2} \left( |\xi|_p^{\frac{2}{p^{1 - \beta}}} + |\eta|_p^{\frac{2}{p^{1 - \beta}}} \right) \]
\[ = 2^{2\beta} e^{\rho_{2^p}} \| \Xi_1 \|_{p, -\beta} \| \Xi_2 \|_{p, -\beta} \exp \left\{ \left((1 - \beta)2^{\frac{2\beta}{1 - \beta}} + \frac{\rho_{2^p}}{2}\right) \left( |\xi|_p^{\frac{2}{p^{1 - \beta}}} + |\eta|_p^{\frac{2}{p^{1 - \beta}}} \right) \right\}. \quad (3.2) \]
Thus $\Theta$ satisfies condition (O2) in Theorem 2.1, and hence there exists $\Xi \in \mathcal{L}((E)_\beta, (E)_\beta)^*$ whose symbol is $\Theta$.

The operator $\Xi$ defined in Lemma 3.1 above is denoted as

$$\Xi = \Xi_1 \circ \Xi_2$$

and is called the *Wick product*. By definition

$$\langle\langle (\Xi_1 \circ \Xi_2) \phi_\xi, \phi_\eta \rangle\rangle = \langle\langle \Xi_1 \phi_\xi, \phi_\eta \rangle\rangle \langle\rangle \langle\langle \Xi_2 \phi_\xi, \phi_\eta \rangle\rangle e^{-\langle\xi, \eta\rangle}. \quad (3.3)$$

**Remark** In terms of Wick symbols one has

$$(\Xi_1 \circ \Xi_2)(\xi, \eta) = \Xi_1(\xi, \eta)\Xi_2(\xi, \eta),$$

which is slightly simpler than (3.1). However, to avoid confusion we use hereafter only operator symbols.

Here are some algebraic properties of the Wick product. The proofs follow directly from (3.3).

$$\Xi \circ I = \Xi \quad (3.4)$$
$$\Xi_1 \circ \Xi_2 = \Xi_2 \circ \Xi_1 \quad (3.5)$$
$$(\Xi_1 \circ \Xi_2) \circ \Xi_3 = \Xi_1 \circ (\Xi_2 \circ \Xi_3) \quad (3.6)$$
$$\Xi_1 \circ \Xi_2^* = \Xi_1^* \circ \Xi_2^* \quad (3.7)$$

**Proposition 3.2** The Wick product is a separately continuous bilinear map from $\mathcal{L}((E)_\beta, (E)_\beta)^* \times \mathcal{L}((E)_\beta, (E)_\beta)^*$ into $\mathcal{L}((E)_\beta, (E)_\beta)^*$.

**Proof.** Suppose $\Xi_1, \Xi_2 \in \mathcal{L}((E)_\beta, (E)_\beta)^*$ and put $\Xi = \Xi_1 \circ \Xi_2$. It follows from (3.2) that

$$|\Xi(\xi, \eta)| \leq C \|\Xi_1\|_{-p,-\beta} \|\Xi_2\|_{-p,-\beta} \exp K \left( |\xi|^{\frac{2}{p^{1-\beta}}} + |\eta|^{\frac{2}{p^{1-\beta}}} \right)$$

for some $C \geq 0$ and $K \geq 0$. Then, observing the proof of Theorem 2.2 carefully, we see that for any $p \geq 0$ there exist $C' \geq 0$ and $q \geq 0$ such that

$$\|\Xi_1 \circ \Xi_2\|_{-(p+q)} \leq C' \|\Xi_1\|_{-p} \|\Xi_2\|_{-p}, \quad \Xi_1, \Xi_2 \in \mathcal{L}_p((E)_\beta, (E)_\beta)^*. \quad (3.8)$$

Suppose $\Xi_2$ is fixed. Then (3.8) means that $\Xi_1 \mapsto \Xi_1 \circ \Xi_2$ is a continuous linear map from $\mathcal{L}_p((E)_\beta, (E)_\beta)^*$ into $\mathcal{L}_{p+q}((E)_\beta, (E)_\beta)^*$, and hence into $\mathcal{L}((E)_\beta, (E)_\beta)^*$. Since

$$\mathcal{L}((E)_\beta, (E)_\beta)^* \cong \operatorname{ind lim}_{p \to \infty} \mathcal{L}_p((E)_\beta, (E)_\beta)^*,$$

$\Xi_1 \mapsto \Xi_1 \circ \Xi_2$ is a continuous linear map from $\mathcal{L}((E)_\beta, (E)_\beta)^*$ into itself.

**Proposition 3.3** For an operator $\Omega \in \mathcal{L}((E)_\beta, (E)_\beta)^*$ the following conditions are equivalent:

(i) $\Xi \circ \Omega = \Xi \Omega$ for any $\Xi \in \mathcal{L}((E)_\beta, (E)_\beta)^*$;
(ii) $\Omega^* \circ \Xi = \Omega^* \Xi$ for any $\Xi \in \mathcal{L}((E)_\beta, (E)_\beta)$;
(iii) the Fock expansion of $\Omega$ contains only annihilation operators, i.e., is of the form:

$$\Omega = \sum_{m=0}^\infty \Xi_{0,m}(\kappa_{0,m}).$$

In that case, if $\Omega \in \mathcal{L}((E)_\beta, (E)_\beta)$ in addition, then $\Xi \circ \Omega = \Xi \Omega$ for any $\Xi \in \mathcal{L}((E)_\beta, (E)_\beta^*)$.

**Proof.** (i) $\iff$ (ii) is obvious because these are obtained by duality from each other.

(i) $\implies$ (iii) Put

$$\Omega = \Xi_{0,1}(\zeta) = \int_{\mathbb{R}} \zeta(t) a(t) dt, \quad \zeta \in E_{\mathbb{C}}.$$

Then

$$(\Xi_{0,1}(\zeta) \circ \Xi)(\xi, \eta) = \tilde{\Xi}_{0,1}(\zeta)(\xi, \eta) \tilde{\Xi}(\xi, \eta) e^{-\langle \xi, \eta \rangle} = \langle \zeta, \xi \rangle \tilde{\Xi}(\xi, \eta) = \langle \Xi \Xi_{0,1}(\zeta) \phi_{\xi}, \phi_{\eta} \rangle.$$

Since $\Xi \circ \Xi_{0,1}(\zeta) = \Xi \Xi_{0,1}(\zeta)$ by assumption, we obtain

$$\Xi_{0,1}(\zeta) \Xi = \Xi \Xi_{0,1}(\zeta), \quad \zeta \in E_{\mathbb{C}}.$$

It is proved [17] that any operator commuting with $\Xi_{0,1}(\zeta)$ contains no creation operators in its Fock expansion.

(iii) $\implies$ (i) Assume that $\Xi = \sum_{m=0}^\infty \Xi_{0,m}(\kappa_{0,m})$. Then for $\Omega \in \mathcal{L}((E)_\beta^*, (E)_\beta^*)$,

$$(\Omega \Xi)^\wedge(\xi, \eta) = \sum_{m=0}^\infty \langle \Omega \Xi_{0,m}(\kappa_{0,m}) \phi_{\xi}, \phi_{\eta} \rangle$$

$$= \sum_{m=0}^\infty \langle \kappa_{0,m}, \xi^{\otimes m} \rangle \langle \Omega \phi_{\xi}, \phi_{\eta} \rangle$$

$$= \sum_{m=0}^\infty \langle \Xi_{0,m}(\kappa_{0,m}) \phi_{\xi}, \phi_{\eta} \rangle e^{-\langle \xi, \eta \rangle} \langle \Omega \phi_{\xi}, \phi_{\eta} \rangle.$$

This implies that $\Omega \Xi = \Omega \circ \Xi$.

Finally, assume that $\Omega = \sum_{m=0}^\infty \Xi_{0,m}(\kappa_{0,m}) \in \mathcal{L}((E)_\beta, (E)_\beta)$. Then, since the series converges in $\mathcal{L}((E)_\beta, (E)_\beta)$, we have

$$(\Xi \Omega)^\wedge(\xi, \eta) = \langle \Xi \Omega \phi_{\xi}, \phi_{\eta} \rangle$$

$$= \sum_{m=0}^\infty \langle \Xi \Xi_{0,m}(\kappa_{0,m}) \phi_{\xi}, \phi_{\eta} \rangle$$

$$= \sum_{m=0}^\infty \langle \kappa_{0,m}, \xi^{\otimes m} \rangle \langle \Xi \phi_{\xi}, \phi_{\eta} \rangle$$

$$= \tilde{\Xi}(\xi, \eta) e^{-\langle \xi, \eta \rangle} \Omega(\xi, \eta).$$

Consequently, $\Xi \circ \Omega = \Xi \Omega$. qed

A similar assertion as above has appeared in Huang–Luo [10].
Corollary 3.4 For any $\Xi \in \mathcal{L}((E)_{\beta}, (E)_{\beta}^{*})$ it holds that
\[ a_{s_1}^{*} \cdots a_{s_\iota}^{*} \Xi a_{t_1} \cdots a_{t_m} = \Xi \circ (a_{s_1}^{*} \cdots a_{s_\iota}^{*} a_{t_1} \cdots a_{t_m}) . \]
In particular,
\[ a_{s}^{*} \Xi = \Xi \circ a_{s}^{*} , \quad \Xi a_{t} = \Xi \circ a_{t} , \]
and
\[ a_s \circ a_t = a_s a_t , \quad a_s^{*} \circ a_t = a_s^{*} a_t , \quad a_s \circ a_t^{*} = a_s a_t^{*} , \quad a_s^{*} \circ a_t^{*} = a_s^{*} a_t^{*} . \]

4 Wick exponential function

Given $\Xi \in \mathcal{L}((E)_{\beta}, (E)_{\beta}^{*})$ with Fock expansion
\[ \Xi = \sum_{l,m=0}^{\infty} \Xi_{l,m}(\kappa_{l,m}) , \]
we put $\deg \Xi = \sup \{ l + m ; \kappa_{l,m} \neq 0 \}$. It can happen that $\deg \Xi = \infty$. For simplicity we put
\[ \Xi^{\infty} = \Xi \circ \cdots \circ \Xi , \quad \Xi^{\infty_0} = I . \]

Theorem 4.1 Let $\Xi \in \mathcal{L}((E), (E)^{*})$. Then
\[ \sum_{n=0}^{\infty} \frac{1}{n!} \Xi^{\infty_n} \]
converges in $\mathcal{L}((E)_{\beta}, (E)_{\beta}^{*})$ if and only if $\deg \Xi \leq 2/(1 - \beta)$. In particular, (4.1) converges in $\mathcal{L}((E), (E)^{*})$ if and only if $\deg \Xi \leq 2$.

PROOF. Given $\Xi \in \mathcal{L}((E), (E)^{*})$ we consider the partial sum:
\[ S_N = \sum_{n=0}^{N} \frac{1}{n!} \Xi^{\infty_n} . \]

In view of a general formula:
\[ (\Xi_1 \circ \cdots \circ \Xi_n)^\wedge (\xi, \eta) = \hat{S}_1(\xi, \eta) \cdots \hat{S}_n(\xi, \eta) e^{-\langle (n - 1)\xi, \eta \rangle} , \]
we have
\[ \hat{S}_N(\xi, \eta) = \sum_{n=0}^{N} \frac{1}{n!} \left( \hat{\Xi}(\xi, \eta) \right)^n e^{-\langle (n - 1)\xi, \eta \rangle} = \sum_{n=0}^{N} \frac{1}{n!} \left( \hat{\Xi}(\xi, \eta) e^{-\langle \xi, \eta \rangle} \right)^n e^{\langle \xi, \eta \rangle} , \]
and hence
\[ \lim_{N \to \infty} \hat{S}_N(\xi, \eta) = \exp(\hat{\Xi}(\xi, \eta) e^{-\langle \xi, \eta \rangle} + \langle \xi, \eta \rangle) , \quad \xi, \eta \in E_{\mathbb{C}} . \]
Then by Theorem 2.3, $S_N$ converges in $\mathcal{L}((E)_\beta, (E)_\beta^*)$ if and only if there exist some constant numbers $C \geq 0$, $K \geq 0$ and $p \geq 0$ such that
\[
|\exp(\mathcal{E}(\xi, \eta)e^{-(\xi, \eta)} + (\xi, \eta))| \leq C \exp K \left( |\xi|^\frac{2}{p^{1-\beta}} + |\eta|^\frac{2}{p^{1-\beta}} \right)
\]
or equivalently, such that
\[
|\exp(\mathcal{E}(\xi, \eta)e^{-(\xi, \eta)} + (\xi, \eta))| \leq C \exp K \left( |\xi|^\frac{2}{p^{1-\beta}} + |\eta|^\frac{2}{p^{1-\beta}} \right). \tag{4.2}
\]
First we assume that $d \equiv \deg \Xi \leq 2/(1 - \beta)$. Choose $p \geq 0$ such that
\[
K' = \max_{l+m \leq d} |\kappa_{l,m}|_{-p} < \infty.
\]
Since the symbol of $\Xi$ is of the form:
\[
\mathcal{E}(\xi, \eta) = \sum_{l+m \leq d} \langle \kappa_{l,m}, \eta^{\otimes l} \otimes \xi^{\otimes m} \rangle e^{(\xi, \eta)},
\]
we have
\[
|\exp(\mathcal{E}(\xi, \eta)e^{-(\xi, \eta)} + (\xi, \eta))| \leq \exp \left\{ \sum_{l+m \leq d} \left| \kappa_{l,m}, \eta^{\otimes l} \otimes \xi^{\otimes m} \right| \right\}
\]
\[
\leq \exp \left\{ \sum_{l+m \leq d} \left| \kappa_{l,m} \right|_{-p} \left| \eta \right|_{p}^{l} \left| \xi \right|_{p}^{m} \right\}
\]
\[
\leq \exp \left\{ K' \sum_{l+m \leq d} \left| \eta \right|_{p}^{l} \left| \xi \right|_{p}^{m} \right\}. \tag{4.3}
\]
Using an obvious inequality $a^{l}b^{m} \leq a^{l+m} + b^{l+m}$, $a, b \geq 0$, we have
\[
\sum_{l+m = k} \left| \eta \right|_{p}^{l} \left| \xi \right|_{p}^{m} \leq \sum_{l+m = k} \left( \left| \eta \right|_{p}^{l+m} + \left| \xi \right|_{p}^{l+m} \right) = (k+1)(\left| \eta \right|_{p}^{k} + \left| \xi \right|_{p}^{k}).
\]
Then (4.3) becomes
\[
|\exp(\mathcal{E}(\xi, \eta)e^{-(\xi, \eta)} + (\xi, \eta))| \leq \exp \left\{ K' \sum_{k=0}^{d} \sum_{l+m = k} \left| \eta \right|_{p}^{l} \left| \xi \right|_{p}^{m} \right\}
\]
\[
\leq \exp \left\{ K' \sum_{k=0}^{d} (k+1)(\left| \eta \right|_{p}^{k} + \left| \xi \right|_{p}^{k}) \right\}
\]
\[
\leq \exp \left\{ K'(d+1) \sum_{k=0}^{d} (\left| \eta \right|_{p}^{k} + \left| \xi \right|_{p}^{k}) \right\}. \tag{4.4}
\]
In view of an inequality $1 + a + a^2 + \cdots + a^d \leq 1 + d + da^d$, $a \geq 0$, (4.4) becomes
\[
\leq \exp \left\{ K'(d+1)(1 + d + d \left| \eta \right|_{p}^{d} + 1 + d + d \left| \xi \right|_{p}^{d}) \right\}
\]
\[
= \exp \left\{ 2K'(d+1)^2 + K'(d+1)d(\left| \eta \right|_{p}^{d} + \left| \xi \right|_{p}^{d}) \right\}. \tag{4.5}
\]
We put
\[ C' = \exp \left(2K'(d+1)^2 \right). \]

Since \( d \leq 2/(1 - \beta) \), we have \( |\eta|^d_p \leq 1 + |\eta|^{2/(1-\beta)} \). Hence (4.5) becomes
\[ \leq C' \exp \left\{ K'(d+1)d(2 + |\eta|^{\frac{2}{p^{1-\beta}}} + |\xi|^{\frac{2}{p^{1-\beta}}}) \right\}. \]

Finally we put
\[ C = C' \exp(2d(d+1)K'), \quad K = K'(d+1)d. \]

We obtain
\[ \exp(\bar{Z}(\xi, \eta)e^{-\langle \xi, \eta \rangle}) \leq C \exp K \left(|\eta|^{\frac{2}{p^{1-\beta}}} + |\xi|^{\frac{2}{p^{1-\beta}}} \right). \]

Hence (4.2) is fulfilled.

Conversely we assume (4.2). For simplicity we put
\[ \theta(z) = \bar{Z}(z\xi, \eta)e^{-\langle \xi, \eta \rangle}, \quad z \in \mathbb{C}. \]

Then \( F(z) = e^{\theta(z)} \) becomes an entire holomorphic function without zeroes of order \( \leq 2/(1 - \beta) \). It then follows from Lemma 4.2 below that \( \theta(z) \) is a polynomial of degree \( \leq 2/(1 - \beta) \), i.e., \( \Xi_{l,m}(\kappa_{l,m}) = 0 \) whenever \( l > 2/(1 - \beta) \). Similarly, we see that \( \Xi_{l,m}(\kappa_{l,m}) = 0 \) whenever \( m > 2/(1 - \beta) \), and hence \( d = \deg \Xi < \infty \). We shall show that \( d \leq 2/(1 - \beta) \). By definition \( \kappa_{l,m} \neq 0 \) for some \( l, m \) with \( l + m = d \). Hence there exist \( \xi, \eta \in E_{\mathbb{C}} \) such that
\[ \omega = \sum_{l+m=d} \langle \kappa_{l,m}, \eta^{l} \otimes \xi^{m} \rangle \neq 0. \]

We may assume without loss of generality that \( \omega > 0 \). In that case (4.2) implies that
\[ \exp \left\{ \sum_{l+m\leq d} \langle \kappa_{l,m}, \eta^{l} \otimes \xi^{m} \rangle \right\} \leq C \exp K \left(|\eta|^{\frac{2}{p^{1-\beta}}} + |\xi|^{\frac{2}{p^{1-\beta}}} \right). \]

Hence for any \( z \in \mathbb{C} \) we have
\[ \exp \left\{ \sum_{l+m\leq d} \langle \kappa_{l,m}, \eta^{l} \otimes \xi^{m} \rangle z^{l+m} \right\} \leq C \exp K|z|^\frac{2}{1-\beta} \left(|\eta|^{\frac{2}{p^{1-\beta}}} + |\xi|^{\frac{2}{p^{1-\beta}}} \right), \]

namely,
\[ \exp \left\{ \omega z^d + P_{d-1}(z) \right\} \leq C \exp \left(\omega' |z|^\frac{2}{1-\beta} \right), \quad (4.6) \]

where
\[ \omega' = K \left(|\eta|^{\frac{2}{p^{1-\beta}}} + |\xi|^{\frac{2}{p^{1-\beta}}} \right) > 0 \]

and \( P_{d-1}(z) \) is a polynomial in \( z \) of degree at most \( d - 1 \). Then (4.6) becomes
\[ \exp \left\{ \omega z^d + P_{d-1}(z) - \omega' |z|^\frac{2}{1-\beta} \right\} \leq C. \quad (4.7) \]

Inequality (4.7) holds for any \( z \in \mathbb{C} \) and hence for any \( z = t > 0 \). Obviously this can happen only when \( d \leq 2/(1 - \beta) \). qed
Lemma 4.2 Let $F(z)$ be an entire holomorphic function with no zeroes in $\mathbb{C}$ of finite order $\alpha \geq 0$, where
\[
\alpha = \limsup_{r \to \infty} \frac{\log \log M(r)}{\log r}, \quad M(r) = \max_{|z| = r} |F(z)|.
\]
Then there exists a polynomial $P(z)$ of degree $\leq \alpha$ such that $F(z) = e^{P(z)}$.

PROOF. This is a simple consequence from Hadamard's factorization theorem for entire holomorphic functions, see e.g., Ahlfors [3].

The convergent series introduced in Theorem 4.1 is called the Wick exponential function of $\Xi$ and is denoted by
\[
\text{wexp } \Xi = \sum_{n=0}^{\infty} \frac{1}{n!} \Xi^n.
\]
Note that the Wick exponential is defined only $\Xi \in \mathcal{L}((E), (E)^*)$ with finite degree, or equivalently, only for finite sums of integral kernel operators.

Lemma 4.3 Let $\Xi_i \in \mathcal{L}((E), (E)^*)$ with $\deg \Xi_i < \infty$, $i = 1, 2$. Then
\[
(w\exp \Xi_1) \circ (w\exp \Xi_2) = w\exp (\Xi_1 + \Xi_2).
\]
In particular,
\[
w\exp \Xi \circ w\exp (-\Xi) = I.
\]

PROOF. In view of definition we observe that
\[
((w\exp \Xi_1) \circ (w\exp \Xi_2))^{(\xi, \eta)} = (w\exp \Xi_1)^{(\xi, \eta)} \cdot (w\exp \Xi_2)^{(\xi, \eta)} 
\]
\[
= e^{(\xi, \eta)} \exp (\Xi_1^{(\xi, \eta)} e^{-(\xi, \eta)}) \cdot e^{(\xi, \eta)} \exp (\Xi_2^{(\xi, \eta)} e^{-(\xi, \eta)}) 
\]
\[
= e^{(\xi, \eta)} \exp ((\Xi_1^{(\xi, \eta)} + \Xi_2^{(\xi, \eta)}) e^{-(\xi, \eta)}) 
\]
\[
= (w\exp (\Xi_1 + \Xi_2))^{(\xi, \eta)}.
\]
Then (4.8) follows.

Lemma 4.4 Assume that $\Xi \in \mathcal{L}((E), (E)^*)$ is of finite degree $\leq 2/(1 - \beta)$. Then $z \mapsto w\exp (z\Xi) \in \mathcal{L}((E)_{\beta}, (E)_{\beta}^*)$ is an entire holomorphic and
\[
\frac{d}{dz} w\exp (z\Xi) = \Xi \circ w\exp (z\Xi)
\]
holds in $\mathcal{L}((E)_{\beta}, (E)_{\beta}^*)$.

Lemma 4.5 Assume that $\Xi \in \mathcal{L}((E), (E)^*)$ is of finite degree $\leq 2/(1 - \beta)$. Let $t \mapsto \Xi_t \in \mathcal{L}((E), (E)^*)$ be a continuous map defined on an interval $T \subset \mathbb{R}$. Then $t \mapsto w\exp (\Xi_t) \in \mathcal{L}((E)_{\beta}, (E)_{\beta}^*)$ is continuous. If in addition $t \mapsto \Xi_t \in \mathcal{L}((E), (E)^*)$ is differentiable,
\[
\frac{d}{dt} w\exp (\Xi_t) = \frac{d\Xi}{dt} \circ w\exp (z\Xi)
\]
holds in $\mathcal{L}((E)_{\beta}, (E)_{\beta}^*)$. 
The above lemmas are proved with the help of Theorem 2.2 (iii) by studying the symbol of a wick exponential function:

$(\text{wexp } \Xi)(\xi, \eta) = \exp \left( \langle \xi, \eta \rangle + \Xi(\xi, \eta)e^{-\langle \xi, \eta \rangle} \right)$.

**Remark** Note that $\Xi \mapsto \text{wexp } \Xi$ is not continuous. In fact, the Wick exponential is defined only for $\Xi$ with finite degree and such operators do not constitute an open set in $\mathcal{L}((E),(E)^*)$.

**Remark** In the recent paper Cochran–Kuo–Sengupta [7] they introduced a further generalization of white noise functions. It is plausible that the Wick exponential $\text{wexp } \Xi$ converges for any $\Xi \in \mathcal{L}((E),(E)^*)$ in a suitably extended space of operators. A further detailed study in this connection will appear elsewhere.

5 Quantum stochastic differential equations

**Lemma 5.1** Let $\{L_t\} \subset \mathcal{L}((E),(E)^*)$ be a quantum stochastic process, i.e., $t \mapsto L_t$ is continuous for $t \in T$, where $T$ is a time interval. Then the quantum stochastic integral defined by

$$M_t = \int_a^t L_s \, ds$$

is also a quantum stochastic process with $\deg M_t \leq \deg L_t$. Moreover,

$$\frac{dM_t}{dt} = L_t$$

holds in $\mathcal{L}((E),(E)^*)$.

**Proof.** That $M_t$ is a quantum stochastic process satisfying $dM_t/dt = L_t$ is known [18]. Let the Fock expansion of $L_t$ is given as

$$L_t = \sum_{l,m=0}^{\infty} \Xi_{l,m}(\kappa_{l,m}(t)).$$

It is known that the map $t \mapsto \kappa_{l,m}(t)$ is continuous for any $l,m$. Then, obviously

$$\int_a^t \Xi_{l,m}(\kappa_{l,m}(s)) \, ds = \Xi_{l,m}(\lambda_{l,m}(t)), \quad \lambda_{l,m}(t) = \int_a^t \kappa_{l,m}(s) \, ds.$$

Therefore

$$M_t = \int_a^t L_s \, ds = \sum_{l,m=0}^{\infty} \Xi_{l,m}(\lambda_{l,m}(t)),$$

which proves the assertion. qed
Theorem 5.2 Let \( \{L_t\}_{t \in T} \subset \mathcal{L}((E), (E)^*) \) be a quantum stochastic process, where \( T \subset \mathbb{R} \) is an interval containing 0. Assume that there exists a number \( \beta \) with \( 0 \leq \beta < 1 \) such that \( \deg L_t \leq 2/(1 - \beta), \) \( t \in T. \) Then the initial value problem

\[
\begin{cases}
\frac{d\Xi_t}{dt} = \Xi_t \circ L_t \\
\Xi_{t=0} = \Xi_0 \in \mathcal{L}((E), (E)^*)
\end{cases}
\]  

(5.1)

has a unique solution in \( \mathcal{L}((E)_\beta, (E)^*_\beta) \) which is expressed in the form:

\[ \Xi_t = \Xi_0 \circ \text{wexp} \int_0^t L_s ds. \]

PROOF. The assertion follows by combining Lemmas 4.5 and 5.1. qed

Here are a few examples, some of which have appeared in Huang–Luo [10] taking no notice of convergence of wick products or existence of solutions.

Example 1 Let \( \{L_t\} \in \mathcal{L}((E), (E)^*) \) be a quantum stochastic process. Assume that \( \deg L_t \leq 2/(1 - \beta) \) and that the expansion of \( L_t \) involves no creation operators. (In that case \( L_t \in \mathcal{L}((E), (E)) \) follows automatically.) Consider the quantum stochastic differential equation:

\[
\frac{d\Xi_t}{dt} = \Xi_t \circ L_t,
\]

(5.2)

where the right hand side is a usual product. Taking \( \Xi_t L_t = \Xi \circ L_t \) into account, we apply Theorem 5.2. There exists a unique solution in \( \mathcal{L}((E)_\beta, (E)^*_\beta) \) which is given by

\[ \Xi_t = \Xi_0 \circ \text{wexp} \int_0^t L_s ds = \Xi_0 \circ \exp \int_0^t L_s ds. \]

By a more precise argument in terms of an equicontinuous generator one sees that the solution lives in \( \mathcal{L}((E)_\beta, (E)_\beta) \). A similar argument is applied to

\[
\frac{d\Xi_t}{dt} = L_t^* \Xi_t
\]

which is dual to (5.2).

Example 2 As a particular case of Example 1 one may consider

\[
\frac{d\Xi_t}{dt} = \Xi_t a_t, \quad \frac{d\Xi_t}{dt} = a_t^* \Xi_t,
\]

and their linear combination:

\[
\frac{d\Xi_t}{dt} = \omega_1 \Xi_t a_t + \omega_2 a_t^* \Xi_t, \quad \omega_1, \omega_2 \in \mathbb{C}.
\]

(5.3)

Equation (5.3) appears in a problem of quantum stochastic limit of an interacting quantum system [1]. Since

\[ \omega_1 \Xi_t a_t + \omega_2 a_t^* \Xi_t = \Xi_t \circ (\omega_1 a_t + \omega_2 a_t^*) \]
and \( \text{deg}(\omega_1 a_t + \omega_2 a_t^*) \leq 1 \), it follows from Theorem 5.2 that equation (5.3) has a unique solution in \( \mathcal{L}((E), (E)^*) \).

**Example 3** Consider

\[
\frac{d\Xi_t}{dt} = a_t^* \Xi_t a_t. \tag{5.4}
\]

In terms of Wick product we have

\[
\frac{d\Xi_t}{dt} = \Xi_t \circ (a_t^* a_t),
\]

hence the solution to (5.3) is given as

\[
\Xi_t = \Xi_0 \circ \text{wexp} \int_0^t a_s^* a_s \, ds.
\]

Here

\[
\Lambda_t = \int_0^t a_s^* a_s \, ds
\]

is called the *number process* or the *gauge process*. Consequently, the solution becomes

\[
\Xi_t = \Xi_0 \circ \text{wexp} \Lambda_t
\]

and lives in \( \mathcal{L}((E), (E)^*) \).

**Example 4** There is no difficulty of discussing

\[
\frac{d\Xi_t}{dt} = \Xi_t a_t^2 + a_t^{*2} \Xi_t. \tag{5.5}
\]

In fact, since

\[
\Xi a_t^2 + a_t^{*2} \Xi_t = \Xi \circ (a_t^2 + a_t^{*2})
\]

and \( \text{deg}(a_t^2 + a_t^{*2}) = 2 \), equation (5.5) has a unique solution in \( \mathcal{L}((E), (E)^*) \) and is given by

\[
\Xi_t = \Xi_0 \circ \text{wexp} \int_0^t (a_s^2 + a_s^{*2}) \, ds.
\]

**Example 5** Let \( L_t \) and \( M_t \) be quantum stochastic processes in \( \mathcal{L}((E), (E)^*) \) and consider

\[
\frac{d\Xi_t}{dt} = \Xi \circ L_t + M_t. \tag{5.6}
\]

If \( \text{deg} L_t \leq 2/(1 - \beta) \), the solution to (5.6) lies in \( \mathcal{L}((E)_{\beta}, (E)^*_\beta) \) and given as

\[
\Xi_t = \left( \int_0^t M_s \circ \Omega_s^{(1)} \, ds + \Xi_0 \right) \circ \Omega_t,
\]

where

\[
\Omega_t = \text{wexp} \int_0^t L_s \, ds, \quad \Omega_t^{(1)} = \text{wexp} \left( - \int_0^t L_s \, ds \right).
\]
Appendix

Let $X$ be a countable Hilbert space over $\mathbb{R}$ or $\mathbb{C}$. Then there exists a sequence of Hilbert spaces $\{H_p\}_{p=-\infty}^{\infty}$ such that

$$\cdots \subset H_{p+1} \subset H_p \subset \cdots \subset H_0 \subset \cdots \subset H_{-p} \subset H_{-(p+1)} \subset \cdots$$

and

$$X \cong \text{proj lim}_{p \to \infty} H_p, \quad X^* \cong \text{ind lim}_{p \to \infty} H_{-p}.$$ 

If $X$ is a nuclear space, we may assume without loss of generality that the natural injection $H_{p+1} \to H_p$ is of Hilbert–Schmidt type for any $p \geq 0$. We denote by $|\cdot|_p$ the norm of $H_p$.

**Proposition A.1** Let $X$ be a countable Hilbert nuclear space and $H_p$ the same as above. Let $\Omega$ be a locally compact space. Then for a map $f : \Omega \to X^*$ the following two conditions are equivalent:

(i) $f$ is continuous;

(ii) for each $\omega_0 \in \Omega$ there exists $p \geq 0$ such that $f(\omega_0) \in H_{-p}$ and

$$\lim_{\omega \to \omega_0} |f(\omega) - f(\omega_0)|_{-p} = 0.$$ 

In that case for any compact subset $\Omega_0 \subset \Omega$ there exists $p \geq 0$ such that $f : \Omega_0 \to H_{-p}$ is continuous.

**Proof.** (i) $\Rightarrow$ (ii) Let $V \subset \Omega$ be an open neighborhood of $\omega_0$ with compact closure. Since $f$ is continuous, $f(V) \subset X^*$ is compact and hence bounded. Then $f(V) \subset H_{-p}$ is bounded for some $p$. In other words, there exists $M \geq 0$ such that

$$|f(\omega)|_{-p} \leq M, \quad \omega \in V.$$ 

Let $\{e_j\}_{j=1}^{\infty}$ be a complete orthonormal basis of $H_{p+1}$. Then by definition,

$$|f(\omega) - f(\omega_0)|_{-(p+1)}^2 = \sum_{j=1}^{\infty} \langle f(\omega) - f(\omega_0), e_j \rangle^2.$$ 

We note that

$$\langle f(\omega) - f(\omega_0), e_j \rangle^2 \leq |f(\omega) - f(\omega_0)|_{-p}^2 |e_j|_{-p}^2 \leq 4M^2 |e_j|_{-p}^2, \quad \omega \in V.$$ 

Given $\epsilon > 0$ we choose $N$ such that

$$4M^2 \sum_{j>N} |e_j|_{-p}^2 < \frac{\epsilon}{2},$$

which is possible since $H_{p+1} \to H_p$ is of Hilbert–Schmidt type and hence $\sum_{j=1}^{\infty} |e_j|_{-p}^2 < \infty$. On the other hand, $\omega \mapsto \langle f(\omega), e_j \rangle$ is continuous by assumption. Then for each $j = 1, \ldots, N$ one may find an open neighborhood $U_j \subset \Omega$ of $\omega_0$ such that

$$|\langle f(\omega), e_j \rangle - \langle f(\omega_0), e_j \rangle| < \sqrt{\frac{\epsilon}{2N}}, \quad \omega \in U_j.$$
Put $U = V \cap U_1 \cap \cdots \cap U_N$. Then

$$| f(\omega) - f(\omega_0) |^2_{(p+1)} = \sum_{j=1}^{N} \langle f(\omega) - f(\omega_0), e_j \rangle^2 + \sum_{j>N} \langle f(\omega) - f(\omega_0), e_j \rangle^2$$

$$\leq \sum_{j=1}^{N} \frac{\epsilon}{2N} + 4M^2 \sum_{j>N} |e_j|^2_p$$

$$< \frac{\epsilon}{2N} + \frac{\epsilon}{2} = \epsilon, \quad \omega \in U.$$

This is the assertion of (ii).

(ii) $\implies$ (i) The topology of $\mathcal{X}^*$ is defined by the seminorms

$$\| f \|_B = \sup_{\omega \in B} |\langle f, \omega \rangle|, \quad f \in \mathcal{X}^*,$$

where $B$ runs over the bounded subsets of $\mathcal{X}$. Then for any $B$ we have

$$\| f(\omega) - f(\omega_0) \|_B \leq \sup_{\omega \in B} |f(\omega) - f(\omega_0)|_p |\omega|_p$$

$$= |B|_p |f(\omega) - f(\omega_0)|_p \to 0, \quad \omega \to \omega_0,$$

by assumption, which shows that $f$ is continuous at $\omega_0$.

The rest of the statement is already clear.

Corollary A.2 Let $\{x_n\}$ be a sequence in $\mathcal{X}^*$ and let $x \in \mathcal{X}^*$. Then $x_n$ converges to $x$ in $\mathcal{X}^*$ if and only if there exists $p \geq 0$ such that $\lim_{n \to \infty} |x_n - x|_p = 0$.

Proof. Consider $\Omega = \{0, 1, 1/2, 1/3, \cdots \}$ equipped with the relative topology induced from $[0,1]$. Set $f(1/n) = x_n$ and $f(0) = x$ and apply Proposition A.1.

References


