

# HEAT KERNEL ANALYSIS ON INFINITE-DIMENSIONAL HEISENBERG GROUPS

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ABSTRACT. We introduce a class of non-commutative Heisenberg like infinite dimensional Lie groups based on an abstract Wiener space. The Ricci curvature tensor for these groups is computed and shown to be bounded. Brownian motion and the corresponding heat kernel measures,  $\{\nu_t\}_{t>0}$ , are also studied. We show that these heat kernel measures admit: 1) Gaussian like upper bounds, 2) Cameron-Martin type quasi-invariance results, 3) good  $L^p$  – bounds on the corresponding Radon-Nykodim derivatives, 4) integration by parts formulas, and 5) logarithmic Sobolev inequalities. The last three results heavily rely on the boundedness of the Ricci tensor.

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## 1. INTRODUCTION

The aim of this paper is to construct and study properties of heat kernel measures on certain infinite-dimensional Heisenberg groups. In this paper the Heisenberg groups will be constructed from a skew symmetric form on an abstract Wiener space. A typical example of such a group is the Heisenberg group of a symplectic vector space. Before describing our results let us recall some typical heat kernel results for finite-dimensional Riemannian manifolds.

**1.1. A finite-dimensional paradigm.** Let  $(M, g)$  be a complete connected  $n$  – dimensional Riemannian manifold ( $n < \infty$ ),  $\Delta = \Delta_g$  be the Laplace Beltrami operator acting on  $C^2(M)$ , and Ric denote the associated Ricci tensor. Recall (see for example Strichartz [48], Dodziuk [15] and Davies [12]) that the closure,  $\bar{\Delta}$ , of  $\Delta|_{C_c^\infty(M)}$  is self-adjoint on  $L^2(M, dV)$ , where  $dV = \sqrt{g}dx^1 \dots dx^n$  is the Riemann volume measure on  $M$ . Moreover, the semi-group  $P_t := e^{t\bar{\Delta}/2}$  has a symmetric positive integral (heat) kernel,  $p_t(x, y)$ , such that  $\int_M p_t(x, y)dV(y) \leq 1$  for all  $x \in M$  and

$$(1.1) \quad P_t f(x) := \left( e^{t\bar{\Delta}/2} f \right) (x) = \int_M p_t(x, y) f(y) dV(y) \text{ for all } f \in L^2(M).$$

Theorem 1.2 summarizes some of the results that we would like to extend to our infinite-dimensional Heisenberg group setting.

**Notation 1.1.** If  $\mu$  is a probability measure on a measure space  $(\Omega, \mathcal{F})$  and  $f \in L^1(\mu) = L^1(\Omega, \mathcal{F}, \mu)$ , we will often write  $\mu(f)$  for the integral,  $\int_\Omega f d\mu$ .

**Theorem 1.2.** Beyond the assumptions above, let us further assume that  $\text{Ric} \geq kI$  for some  $k \in \mathbb{R}$ . Then

- (1)  $p_t(x, y)$  is a smooth function. (The Ricci curvature assumption is not needed here.)
- (2)  $\int_M p_t(x, y) dV(y) = 1$ , (see for example Davies [12, Theorem 5.2.6]).
- (3) Given a point  $o \in M$ , let  $d\nu_t(x) := p_t(o, x) dV(x)$  for all  $t > 0$ . Then  $\{\nu_t\}_{t>0}$  may be characterized as the unique family of probability measures such that the function  $t \rightarrow \nu_t(f) := \int_M f d\nu_t$  is continuously differentiable,

$$(1.2) \quad \frac{d}{dt} \nu_t(f) = \frac{1}{2} \nu_t(\Delta f), \text{ and } \lim_{t \downarrow 0} \nu_t(f) = f(o)$$

for all  $f \in BC^2(M)$ , the bounded  $C^2$ -functions on  $M$ .

- (4) There exist constants,  $c = c(K, n, T)$  and  $C = C(K, n, T)$ , such that,

$$(1.3) \quad p(t, x, y) \leq \frac{C}{V\left(x, \sqrt{t/2}\right)} \exp\left(-c \frac{d^2(x, y)}{t}\right),$$

for all  $x, y \in M$  and  $t \in (0, T]$ , where  $d(x, y)$  is the Riemannian distance from  $x$  to  $y$  and  $V(x, r)$  is the volume of the  $r$ -ball centered at  $x$ .

- (5) The **heat kernel measure**,  $\nu_T$ , for any  $T > 0$  satisfies the following logarithmic Sobolev inequality;

$$(1.4) \quad \nu_T(f^2 \log f^2) \leq 2k^{-1} (1 - e^{-kT}) \nu_T(|\nabla f|^2) + \nu_T(f^2) \log \nu_T(f^2),$$

for  $f \in C_c^\infty(M)$ .

These results are fairly standard. For item 3. see [17, Theorem 2.6], for Eq. (1.3) see for example Theorems 5.6.4, 5.6.6, and 5.4.12 in Saloff-Coste [47] and for more detailed bounds see [39, 12, 46, 13, 26]). The logarithmic Sobolev inequality in Eq. (1.4) generalizes Gross' [28] original Logarithmic Sobolev inequality valid for  $M = \mathbb{R}^n$  and is due in this generality to D. Bakry and M. Ledoux, see [2, 3, 38]. Also see [30, 10, 52, 51, 21] and Driver and Lohrenz [22, Theorem 2.9] for the case of interest here, namely when  $M$  is a uni-modular Lie group with a left invariant Riemannian metric.

When passing to infinite-dimensional Riemannian manifolds we will no longer have available the Riemannian volume measure. Because of this problem, we will take item 3. of Theorem 1.2 as our definition of the heat kernel measure. The heat kernel upper bound in Eq. (1.3) also does not make sense in infinite dimensions. However, the following consequence almost does: there exists  $c(T) > 0$  such that

$$(1.5) \quad \int_M \exp\left(c \frac{d^2(o, x)}{t}\right) d\nu_t(x) < \infty \text{ for all } 0 < t \leq T.$$

In fact Eq. (1.5) will not hold in infinite dimensions either. It will be necessary to replace the distance function,  $d$ , by a weaker distance function as happens in Fernique's theorem for Gaussian measure spaces. With these results as background we are now ready to summarize the results of this paper.

**1.2. Summary of results.** Let us describe the setting informally, for precise definitions see Sections 2 and 3. Let  $(W, H, \mu)$  be an abstract Wiener space,  $\mathbf{C}$  be a finite-dimensional inner product space, and  $\omega : W \times W \rightarrow \mathbf{C}$  be a continuous skew symmetric bilinear quadratic form on  $W$ . The set  $\mathfrak{g} = W \times \mathbf{C}$  can be equipped with a Lie bracket by setting

$$[(A, a), (B, b)] = (0, \omega(A, B)).$$

As in the case for the Heisenberg group of a symplectic vector space, the Lie algebra  $\mathfrak{g} = W \times \mathbf{C}$  can be given the group structure by defining

$$(w_1, c_1) \cdot (w_2, c_2) = \left( w_1 + w_2, c_1 + c_2 + \frac{1}{2} \omega(w_1, w_2) \right).$$

The set  $W \times \mathbf{C}$  with the group structure will be denoted by  $G$  or  $G(\omega)$ . The Lie subalgebra  $\mathfrak{g}_{CM} = H \times \mathbf{C}$  is called the Cameron-Martin subalgebra, and  $\mathfrak{g}_{CM}$  equipped with the same group multiplication denoted by  $G_{CM}$  and called the Cameron-Martin subgroup. We equip  $G_{CM}$  with the left invariant Riemannian metric which agrees with the natural Hilbert inner product,

$$\langle (A, a), (B, b) \rangle_{\mathfrak{g}_{CM}} := \langle A, B \rangle_H + \langle a, b \rangle_{\mathbf{C}},$$

on  $\mathfrak{g}_{CM} \cong T_e G_{CM}$ . In Section 3 we give several examples of this abstract setting including the standard finite-dimensional Heisenberg group.

The main objects of our study are a Brownian motion in  $G$  and the corresponding heat kernel measure defined in Section 4. Namely, let  $\{(B(t), B_0(t))\}_{t \geq 0}$  be a Brownian motion on  $\mathfrak{g}$  with variance determined by

$$\begin{aligned} \mathbb{E} \left[ \langle (B(s), B_0(s)), (A, a) \rangle_{\mathfrak{g}_{CM}} \cdot \langle (B(t), B_0(t)), (C, c) \rangle_{\mathfrak{g}_{CM}} \right] \\ = \operatorname{Re} \langle (A, a), (C, c) \rangle_{\mathfrak{g}_{CM}} \min(s, t) \end{aligned}$$

for all  $s, t \in [0, \infty)$ ,  $A, C \in H_*$  and  $a, c \in \mathbf{C}$ . Then the Brownian motion on  $G$  is the continuous  $G$ -valued process defined by

$$g(t) = \left( B(t), B_0(t) + \frac{1}{2} \int_0^t \omega(B(\tau), dB(\tau)) \right).$$

For  $T > 0$  the heat kernel measure on  $G$  is  $\nu_T = \operatorname{Law}(g(T))$ . It is shown in Corollary 4.5 that  $\{\nu_t\}_{t > 0}$  satisfies item 3. of Theorem 1.2 with  $o = (0, 0) \in G(\omega)$ .

Theorem 4.16 gives heat kernel measure bounds that may be viewed as a non-commutative version of Fernique's theorem for  $G(\omega)$ . In light of Theorem 3.12 this result is also analogous to the integrated Gaussian upper bound in Eq. (1.5).

In Theorem 5.2 we prove quasi-invariance for the path space measure associated to the Brownian motion,  $g$ , on  $G$  with respect to multiplication on the left by finite energy paths in the Cameron-Martin subgroup  $G_{CM}$ . (In light of the results in Malliavin [40] it is surprising that Theorem 5.2 holds.) Theorem 5.2 is then used to prove quasi-invariance of the heat kernel measures with respect to both right and left multiplication (Theorem 6.1 and Corollary 6.2), as well as integration by parts formulae on the path space and for the heat kernel measures, see Corollaries 5.6 – 6.5. These results can be interpreted as the first steps towards proving  $\nu_t$  is a “strictly positive” smooth measure. In this infinite-dimensional it is natural to interpret quasi-invariance and integration by parts formulae as properties of the smoothness of the heat kernel measure, see [17, Theorem 3.3] for example.

In Section 7 we compute the Ricci curvature and check that not only it is bounded from below (see Proposition 7.2), but also that the Ricci curvature of certain finite-dimensional “approximations” are bounded from below with constants independent of the approximation. Based on results in [18], these bounds allow us to give another proof of the quasi-invariance result for  $\nu_t$  and at the same time to get  $L^p$ - estimates on the corresponding Radon-Nikodym derivatives, see Theorem 8.1. These estimates are crucial for the heat kernel analysis on the spaces of holomorphic functions which is the subject of our paper [19]. In Theorem 8.3 we show that an analogue of the logarithmic Sobolev inequality in Eq. (1.4) holds in our setting as well.

In Section 9 we give a list of open questions and further possible developments of the results of this paper. We expect our methods to be applicable to a much larger class of infinite-dimensional nilpotent groups.

Finally, we refer to papers of H. Airault, P. Malliavin, D. Bell, Y. Inahama concerning quasi-invariance, integration by parts formulae and the logarithmic Sobolev inequality on certain infinite-dimensional curved spaces ([1, 4, 6, 5, 32]).

## 2. ABSTRACT WIENER SPACE PRELIMINARIES

Suppose that  $X$  is a real separable Banach space and  $\mathcal{B}_X$  is the Borel  $\sigma$ -algebra on  $X$ .

**Definition 2.1.** A measure  $\mu$  on  $(X, \mathcal{B}_X)$  is called a (mean zero, non-degenerate) **Gaussian measure** provided that its characteristic functional is given by

$$(2.1) \quad \hat{\mu}(u) := \int_X e^{iu(x)} d\mu(x) = e^{-\frac{1}{2}q(u,u)} \text{ for all } u \in X^*,$$

where  $q = q_\mu : X^* \times X^* \rightarrow \mathbb{R}$  is a quadratic form such that  $q(u, v) = q(v, u)$  and  $q(u) = q(u, u) \geq 0$  with equality iff  $u = 0$ , i.e.  $q$  is a real inner product on  $X^*$ .

In what follows we frequently make use of the fact that

$$(2.2) \quad C_p := \int_X \|x\|_X^p d\mu(x) < \infty \text{ for all } 1 \leq p < \infty.$$

This is a consequence of Skorohod's inequality (see for example [36, Theorem 3.2])

$$(2.3) \quad \int_X e^{\lambda\|x\|_X} d\mu(x) < \infty \text{ for all } \lambda < \infty;$$

or the even stronger Fernique's inequality (see for example [8, Theorem 2.8.5] or [36, Theorem 3.1])

$$(2.4) \quad \int_X e^{\delta\|x\|_X^2} d\mu(x) < \infty \text{ for some } \delta > 0.$$

**Lemma 2.2.** *If  $u, v \in X^*$ , then*

$$(2.5) \quad \int_X u(x) v(x) d\mu(x) = q(u, v)$$

and

$$(2.6) \quad |q(u, v)| \leq C_2 \|u\|_{X^*} \|v\|_{X^*}.$$

*Proof.* Let  $u_*\mu := \mu \circ u^{-1}$  denote the law of  $u$  under  $\mu$ . Then by Equation (2.1),

$$(u_*\mu)(dx) = \frac{1}{\sqrt{2\pi q(u, u)}} e^{-\frac{1}{2q(u, u)}x^2} dx$$

and hence,

$$(2.7) \quad \int_X u^2(x) d\mu(x) = q_\mu(u, u) = q(u, u).$$

Polarizing this identity gives Equation (2.5) which along with Equation (2.2) implies Equation (2.6).  $\square$

The next theorem summarizes some well known properties of Gaussian measures that we will use freely below.

**Theorem 2.3.** *Let  $\mu$  be a Gaussian measure on a real separable Banach space,  $X$ . For  $x \in X$  let*

$$(2.8) \quad \|x\|_H := \sup_{u \in X^* \setminus \{0\}} \frac{|u(x)|}{\sqrt{q(u, u)}}$$

and define the **Cameron-Martin subspace**,  $H \subset X$ , by

$$(2.9) \quad H = \{h \in X : \|h\|_H < \infty\}.$$

Then

- (1)  $H$  is a dense subspace of  $X$ ;

(2) there exists a unique inner product,  $\langle \cdot, \cdot \rangle_H$  on  $H$  such that  $\|h\|_H^2 = \langle h, h \rangle$  for all  $h \in H$ . Moreover, with this inner product  $H$  is a separable Hilbert space.

(3) For any  $h \in H$

$$(2.10) \quad \|h\|_X \leq \sqrt{C_2} \|h\|_H,$$

where  $C_2$  is as in (2.2).

(4) If  $\{e_j\}_{j=1}^\infty$  is an orthonormal basis for  $H$ , then for any  $u, v \in H^*$

$$(2.11) \quad q(u, v) = \langle u, v \rangle_{H^*} = \sum_{j=1}^\infty u(e_j) v(e_j).$$

The proof of this standard theorem is relegated to Appendix A – see Theorem A.1.

**Remark 2.4.** It follows from Equation (2.10) that any  $u \in X^*$  restricted to  $H$  is in  $H^*$ . Therefore we have

$$(2.12) \quad \int_X u^2 d\mu = q(u, u) = \|u\|_{H^*}^2 = \sum_{j=1}^\infty |u(e_j)|^2,$$

where  $\{e_j\}_{j=1}^\infty$  is an orthonormal basis for  $H$ . More generally, if  $\varphi$  is a linear bounded map from  $X$  to  $\mathbf{C}$ , where  $\mathbf{C}$  is a real Hilbert space, then

$$(2.13) \quad \|\varphi\|_{H^* \otimes \mathbf{C}}^2 =: \sum_{j=1}^\infty \|\varphi(e_j)\|_{\mathbf{C}}^2 = \int_X \|\varphi(x)\|_{\mathbf{C}}^2 d\mu(x) < \infty.$$

To prove Equation (2.13), let  $\{f_j\}_{j=1}^\infty$  be an orthonormal basis for  $\mathbf{C}$ . Then

$$\begin{aligned} \int_X \|\varphi(x)\|_{\mathbf{C}}^2 d\mu(x) &= \int_X \sum_{j=1}^\infty |\langle \varphi(x), f_j \rangle_{\mathbf{C}}|^2 d\mu(x) = \sum_{j=1}^\infty \int_X |\langle \varphi(x), f_j \rangle_{\mathbf{C}}|^2 d\mu(x) \\ &= \sum_{j=1}^\infty \|\langle \varphi(\cdot), f_j \rangle_{\mathbf{C}}\|_{H^*}^2 = \sum_{j=1}^\infty \sum_{k=1}^\infty |\langle \varphi(e_k), f_j \rangle_{\mathbf{C}}|^2 \\ &= \sum_{k=1}^\infty \sum_{j=1}^\infty |\langle \varphi(e_k), f_j \rangle_{\mathbf{C}}|^2 = \sum_{k=1}^\infty \|\varphi(e_k)\|_{\mathbf{C}}^2 = \|\varphi\|_{H^* \otimes \mathbf{C}}^2. \end{aligned}$$

A simple consequence of Eq. (2.13) is that

$$(2.14) \quad \|\varphi\|_{H^* \otimes \mathbf{C}}^2 \leq \|\varphi\|_{X^* \otimes \mathbf{C}}^2 \int_X \|x\|_X^2 d\mu(x) = C_2 \|\varphi\|_{X^* \otimes \mathbf{C}}^2.$$

### 3. INFINITE-DIMENSIONAL HEISENBERG TYPE GROUPS

Throughout the rest of this paper  $(X, H, \mu)$  will denote a **real abstract Wiener space**, i.e.  $X$  is a real separable Banach space,  $H$  is a real separable Hilbert space densely embedded into  $X$ , and  $\mu$  is a Gaussian measure on  $(X, \mathcal{B}_X)$  such that Equation (2.1) holds with  $q(u, u) := \langle u|_H, u|_H \rangle_{H^*}$ .

Following the discussion in [35] and [23] we will say that a (possibly infinite-dimensional) Lie algebra,  $\mathfrak{g}$ , is of **Heisenberg type** if  $\mathbf{C} := [\mathfrak{g}, \mathfrak{g}]$  is contained in the center of  $\mathfrak{g}$ . If  $\mathfrak{g}$  is of Heisenberg type and  $W$  is a complementary subspace to

$\mathbf{C}$  in  $\mathfrak{g}$ , we may define a bilinear map,  $\omega : W \times W \rightarrow \mathbf{C}$ , by  $\omega(w, w') = [w, w']$  for all  $w, w' \in W$ . Then for  $\xi_i := w_i + c_i \in W \oplus \mathbf{C} = \mathfrak{g}$ ,  $i = 1, 2$  we have

$$[\xi_1, \xi_2] = [w_1 + c_1, w_2 + c_2] = 0 + \omega(w_1, w_2).$$

If we now suppose  $G$  is a finite-dimensional Lie group with Lie algebra  $\mathfrak{g}$ , then by the Baker-Campbell-Dynkin-Hausdorff formula

$$e^{\xi_1} e^{\xi_2} = e^{\xi_1 + \xi_2 + \frac{1}{2}[\xi_1, \xi_2]} = e^{w_1 + w_2 + c_1 + c_2 + \frac{1}{2}\omega(w_1, w_2)}.$$

In particular, we may introduce a group structure on  $\mathfrak{g}$  by defining

$$(w_1 + c_1) \cdot (w_2 + c_2) = w_1 + w_2 + c_1 + c_2 + \frac{1}{2}\omega(w_1, w_2).$$

With this as motivation, we are now going to introduce a class of Heisenberg type Lie groups based on the following data.

**Notation 3.1.** *Let  $(W, H, \mu)$  be an abstract Wiener space,  $\mathbf{C}$  be a finite-dimensional inner product space, and  $\omega : W \times W \rightarrow \mathbf{C}$  be a continuous skew symmetric bilinear quadratic form on  $W$ . Further let*

$$(3.1) \quad \|\omega\|_0 := \sup \{ \|\omega(w_1, w_2)\|_{\mathbf{C}} : w_1, w_2 \in W \text{ with } \|w_1\|_W = \|w_2\|_W = 1 \}.$$

be the uniform norm on  $\omega$  which is finite by the assumed continuity of  $\omega$ .

We now define  $\mathfrak{g} := W \times \mathbf{C}$  which is a Banach space in the norm

$$(3.2) \quad \|(w, c)\|_{\mathfrak{g}} := \|w\|_W + \|c\|_{\mathbf{C}}.$$

We further define  $\mathfrak{g}_{CM} := H \times \mathbf{C}$  which is a Hilbert space relative to the inner product

$$(3.3) \quad \langle (A, a), (B, b) \rangle_{\mathfrak{g}_{CM}} := \langle A, B \rangle_H + \langle a, b \rangle_{\mathbf{C}}.$$

The associated Hilbertian norm on  $\mathfrak{g}_{CM}$  is given by

$$(3.4) \quad \|(A, a)\|_{\mathfrak{g}_{CM}} := \sqrt{\|A\|_H^2 + \|a\|_{\mathbf{C}}^2}.$$

It is easily checked that defining

$$(3.5) \quad [(w_1, c_1), (w_2, c_2)] := (0, \omega(w_1, w_2))$$

for all  $(w_1, c_1), (w_2, c_2) \in \mathfrak{g}$  makes  $\mathfrak{g}$  into a Lie algebra such that  $\mathfrak{g}_{CM}$  is Lie subalgebra of  $\mathfrak{g}$ . Note that this definition implies that  $\mathbf{C} = [\mathfrak{g}, \mathfrak{g}]$  is contained in the center of  $\mathfrak{g}$ . It is also easy to verify that we may make  $\mathfrak{g}$  into a group using the multiplication rule

$$(3.6) \quad (w_1, c_1) \cdot (w_2, c_2) = \left( w_1 + w_2, c_1 + c_2 + \frac{1}{2}\omega(w_1, w_2) \right).$$

The latter equation may be more simply expressed as

$$(3.7) \quad g_1 g_2 = g_1 + g_2 + \frac{1}{2}[g_1, g_2],$$

where  $g_i = (w_i, c_i)$ ,  $i = 1, 2$ . As sets  $G$  and  $\mathfrak{g}$  are the same.

The identity in  $G$  is  $\mathbf{e} = (0, 0)$  and the inverse is given by  $g^{-1} = -g$  for all  $g = (w, c) \in G$ . Let us observe that  $\{0\} \times \mathbf{C}$  is in the center of both  $G$  and  $\mathfrak{g}$  and for  $h$  in the center of  $G$ ,  $g \cdot h = g + h$ . In particular, since  $[g, h] \in \{0\} \times \mathbf{C}$  it follows that  $k \cdot [g, h] = k + [g, h]$  for all  $k, g, h \in G$ .

**Definition 3.2.** When we want to emphasize the group structure on  $\mathfrak{g}$  we denote  $\mathfrak{g}$  by  $G$  or  $G(\omega)$ . Similarly, when we view  $\mathfrak{g}_{CM}$  as a subgroup of  $G$  it will be denoted by  $G_{CM}$  and will be called the **Cameron–Martin** subgroup.

**Lemma 3.3.** *The Banach space topologies on  $\mathfrak{g}$  and  $\mathfrak{g}_{CM}$  make  $G$  and  $G_{CM}$  into topological groups.*

*Proof.* Since  $g^{-1} = -g$ , the map  $g \mapsto g^{-1}$  is continuous in the  $\mathfrak{g}$  and  $\mathfrak{g}_{CM}$  topologies. Since  $(g_1, g_2) \mapsto g_1 + g_2$  and  $(g_1, g_2) \mapsto [g_1, g_2]$  are continuous in both the  $\mathfrak{g}$  and  $\mathfrak{g}_{CM}$  topologies, it follows from Equation (3.7) that  $(g_1, g_2) \mapsto g_1 \cdot g_2$  is continuous as well.  $\square$

For later purposes it is useful to observe, by Equations (3.5) and (3.7), that

$$(3.8) \quad \|g_1 g_2\|_{\mathfrak{g}} \leq \|g_1\|_{\mathfrak{g}} + \|g_2\|_{\mathfrak{g}} + \frac{1}{2} \|\omega\|_0 \|g_1\|_{\mathfrak{g}} \|g_2\|_{\mathfrak{g}} \text{ for any } g_1, g_2 \in G.$$

**Notation 3.4.** *To each  $g \in G$ , let  $l_g : G \rightarrow G$  and  $r_g : G \rightarrow G$  denote left and right multiplication by  $g$  respectively.*

**Notation 3.5** (Linear differentials). *Suppose  $f : G \rightarrow \mathbb{C}$  is a Fréchet smooth function. For  $g \in G$  and  $h, k \in \mathfrak{g}$  let*

$$f'(g)h := \partial_h f(g) = \left. \frac{d}{dt} \right|_0 f(g + th)$$

and

$$f''(g)(h \otimes k) := \partial_h \partial_k f(g).$$

Here and in the sequel a prime on a symbol will be used denote its derivative or differential.

As  $G$  is a vector space, to each  $g \in G$  we can associate the tangent space (as in the following notation) to  $G$  at  $g$ ,  $T_g G$ , which is naturally isomorphic to  $G$ .

**Notation 3.6.** *For  $v, g \in G$ , let  $v_g \in T_g G$  denote the tangent vector satisfying,  $v_g f = f'(g)v$  for all Fréchet smooth functions,  $f : G \rightarrow \mathbb{C}$ .*

We will write  $\mathfrak{g}$  and  $\mathfrak{g}_{CM}$  for  $T_e G$  and  $T_e G_{CM}$  respectively. Of course as sets we may view  $\mathfrak{g}$  and  $\mathfrak{g}_{CM}$  as  $G$  and  $G_{CM}$  respectively. For  $h \in \mathfrak{g}$ , let  $\tilde{h}$  be the **left invariant vector field** on  $G$  such that  $\tilde{h}(g) = h$  when  $g = \mathbf{e}$ . More precisely if  $\sigma(t) \in G$  is any smooth curve such that  $\sigma(0) = \mathbf{e}$  and  $\dot{\sigma}(0) = h$  (e.g.  $\sigma(t) = th$ ), then

$$(3.9) \quad \tilde{h}(g) = l_{g*} h := \left. \frac{d}{dt} \right|_0 g \cdot \sigma(t).$$

As usual we view  $\tilde{h}$  as a first order differential operator acting on smooth functions,  $f : G \rightarrow \mathbb{C}$ , by

$$(3.10) \quad (\tilde{h}f)(g) = \left. \frac{d}{dt} \right|_0 f(g \cdot \sigma(t)).$$

**Proposition 3.7.** *Let  $f : G \rightarrow \mathbb{C}$  be a smooth function,  $h = (A, a) \in \mathfrak{g}$  and  $g = (w, c) \in G$ . Then*

$$(3.11) \quad \tilde{h}(g) := l_{g*} h = \left( A, a + \frac{1}{2} \omega(w, A) \right)_g \text{ for all } g = (w, c) \in G$$



and in particular using Notation 3.6

$$(3.12) \quad \widetilde{(A, a)}f(g) = f'(g) \left( A, a + \frac{1}{2}\omega(w, A) \right).$$

Furthermore, if  $h = (A, a)$ ,  $k = (B, b)$ , and then

$$(3.13) \quad \left( \tilde{h}\tilde{k}f - \tilde{k}\tilde{h}f \right) = \widetilde{[h, k]}f.$$

In other words, the Lie algebra structure on  $\mathfrak{g}$  induced by the Lie algebra structure on the left invariant vector fields on  $G$  is the same as the Lie algebra structure defined in Eq. (3.5).

*Proof.* Since  $th = t(A, a)$  is a curve in  $G$  passing through the identity at  $t = 0$ , we have

$$\begin{aligned} \tilde{h}(g) &= \left. \frac{d}{dt} \right|_0 [g \cdot (th)] = \left. \frac{d}{dt} \right|_0 [(w, c) \cdot t(A, a)] \\ &= \left. \frac{d}{dt} \right|_0 \left[ \left( w + tA, c + ta + \frac{t}{2}\omega(w, A) \right) \right] \\ &= \left( A, a + \frac{1}{2}\omega(w, A) \right). \end{aligned}$$

So by the chain rule,  $(\tilde{h}f)(g) = f'(g)\tilde{h}(g)$  and hence

$$(3.14) \quad \begin{aligned} (\tilde{h}\tilde{k}f)(g) &= \left. \frac{d}{dt} \right|_0 [f'(g \cdot th)\tilde{k}(g \cdot th)] \\ &= f''(g) \left( \tilde{h}(g) \otimes \tilde{k}(g) \right) + f'(g) \left. \frac{d}{dt} \right|_0 \tilde{k}(g \cdot th), \end{aligned}$$

where

$$\left. \frac{d}{dt} \right|_0 \tilde{k}(g \cdot th) = \left. \frac{d}{dt} \right|_0 \left( B, a + \frac{1}{2}\omega(w + tA, B) \right) = \left( 0, \frac{1}{2}\omega(A, B) \right).$$

Since  $f''(g)$  is symmetric, it now follows by subtracting Equation (3.14) with  $h$  and  $k$  interchanged from itself that

$$\left( \tilde{h}\tilde{k}f - \tilde{k}\tilde{h}f \right)(g) = f'(g) \left( 0, \omega(A, B) \right) = f'(g) [h, k] = \left( \widetilde{[h, k]}f \right)(g)$$

as desired.  $\square$

**Lemma 3.8.** *The one parameter group in  $G$ ,  $e^{th}$ , determined by  $h = (A, a) \in \mathfrak{g}$ , is given by*

$$(3.15) \quad e^{th} = th = t(A, a).$$

*Proof.* Letting  $(w(t), c(t)) := e^{th}$ , according to Equation (3.11) we have that

$$\left. \frac{d}{dt} \right|_0 (w(t), c(t)) = \left( A, a + \frac{1}{2}\omega(w(t), A) \right) \text{ with } w(0) = 0 \text{ and } c(0) = 0.$$

The solution to this differential equation is easily seen to be given by Equation (3.15).  $\square$

### 3.1. Length and distance estimates.

**Notation 3.9.** Let  $T > 0$  and  $C_{CM}^1$  denote the collection of  $C^1$ -paths,  $g : [0, T] \rightarrow G_{CM}$ . The length of  $g$  is defined as

$$(3.16) \quad \ell_{G_{CM}}(g) = \int_0^T \|l_{g^{-1}(s)*}g'(s)\|_{\mathfrak{g}_{CM}} ds.$$

As usual, the Riemannian distance between  $x, y \in G_{CM}$  is defined as

$$d_{G_{CM}}(x, y) = \inf \{ \ell_{G_{CM}}(g) : g \in C_{CM}^1 \text{ such that } g(0) = x \text{ and } g(T) = y \}.$$

It will also be convenient to define  $|y| := d_{G_{CM}}(\mathbf{e}, y)$  for all  $y \in G_{CM}$ . (The value of  $T > 0$  used in defining  $d_{G_{CM}}$  is irrelevant since the length functional is reparametrization invariant.)

Let

$$(3.17) \quad C := \sup \{ \|\omega(h, k)\|_{\mathbf{C}} : \|h\|_H = \|k\|_H = 1 \} \leq C_2 \|\omega\|_0 < \infty.$$

The inequality in Eq. (3.17) is a consequence of Eq. (2.10) and the definition of  $\|\omega\|_0$  in Eq. (3.1).

**Proposition 3.10.** Let  $\varepsilon := 1/C$  where  $C$  is as in Eq. (3.17). Then for all  $x, y \in G_{CM}$ ,

$$(3.18) \quad d_{G_{CM}}(x, y) \leq \left( 1 + \frac{C}{2} \|x\|_{\mathfrak{g}_{CM}} \wedge \|y\|_{\mathfrak{g}_{CM}} \right) \|y - x\|_{\mathfrak{g}_{CM}}$$

and in particular,  $|x| = d_{G_{CM}}(\mathbf{e}, x) \leq \|x\|_{\mathfrak{g}_{CM}}$ . Moreover, there exists  $K < \infty$  such that if  $x, y \in G_{CM}$  with  $d_{G_{CM}}(x, y) < \varepsilon/2 = 1/2C$ , then

$$(3.19) \quad \|y - x\|_{\mathfrak{g}_{CM}} \leq K \left( 1 + \|x\|_{\mathfrak{g}_{CM}} \wedge \|y\|_{\mathfrak{g}_{CM}} \right) d_{G_{CM}}(x, y).$$

As a consequence of Eqs. (3.18) and (3.19) we see that the topology on  $G_{CM}$  induced by  $d_{G_{CM}}$  is the same as the Hilbert topology induced by  $\|\cdot\|_{\mathfrak{g}_{CM}}$ .

**Remark 3.11.** The equivalence of these two topologies in an infinite-dimensional setting has been addressed in [24] in the case of Hilbert-Schmidt groups of operators.

*Proof.* For notational simplicity, let  $T = 1$ . If  $g(s) = (w(s), a(s))$  is a path in  $C_{CM}^1$  for  $0 \leq s \leq 1$ , then by Equation (3.11)

$$(3.20) \quad \begin{aligned} l_{g^{-1}(s)*}g'(s) &= \left( w'(s), a'(s) - \frac{1}{2}\omega(w(s), w'(s)) \right) \\ &= g'(s) - \frac{1}{2}[g(s), g'(s)] \end{aligned}$$

and we may write Equation (3.16) more explicitly as

$$(3.21) \quad \ell_{G_{CM}}(g) = \int_0^1 \left\| g'(s) - \frac{1}{2}[g(s), g'(s)] \right\|_{\mathfrak{g}_{CM}} ds.$$

If we now apply Equation (3.21) to  $g(s) = x + s(y - x)$  for  $0 \leq s \leq 1$ , we see that

$$\begin{aligned} d_{G_{CM}}(x, y) &\leq \ell_{G_{CM}}(g) = \int_0^1 \left\| (y - x) - \frac{1}{2}[x + s(y - x), (y - x)] \right\|_{\mathfrak{g}_{CM}} ds \\ &= \left\| (y - x) - \frac{1}{2}[x, (y - x)] \right\|_{\mathfrak{g}_{CM}} \leq \left( 1 + \frac{C}{2} \|x\|_{\mathfrak{g}_{CM}} \right) \|y - x\|_{\mathfrak{g}_{CM}}. \end{aligned}$$

As we may interchange the roles of  $x$  and  $y$  in this inequality, the proof of Equation (3.18) is complete.

Let

$$B_\varepsilon := \left\{ x \in \mathfrak{g}_{CM} : \|x\|_{\mathfrak{g}_{CM}} \leq \varepsilon \right\},$$

$y \in B_\varepsilon$ , and  $g : [0, 1] \rightarrow G_{CM}$  be a  $C^1$ -path such that  $g(0) = (0, 0) = \mathbf{e}$  and  $g(1) = y$ . Further let  $T \in [0, 1]$  be the first time that  $g$  exits  $B_\varepsilon$  with the convention that  $T = 1$  if  $g([0, 1]) \subset B_\varepsilon$ . Then from Equation (3.21)

$$\begin{aligned} \ell_{G_{CM}}(g) &\geq \ell_{G_{CM}}(g|_{[0, T]}) \\ &\geq \int_0^T \left[ \|g'(s)\|_{\mathfrak{g}_{CM}} - \frac{1}{2} \|[g(s), g'(s)]\|_{\mathfrak{g}_{CM}} \right] ds \\ &\geq \left(1 - \frac{C}{2}\varepsilon\right) \cdot \int_0^T \|g'(s)\|_{\mathfrak{g}_{CM}} ds \geq \left(1 - \frac{C}{2}\varepsilon\right) \cdot \|g(T)\|_{\mathfrak{g}_{CM}} \\ (3.22) \quad &\geq \frac{1}{2} \|g(T)\|_{\mathfrak{g}_{CM}} \geq \frac{1}{2} \|y\|_{\mathfrak{g}_{CM}}. \end{aligned}$$

Optimizing Equation (3.22) over  $g$  implies

$$\|y\| = d_{G_{CM}}(\mathbf{e}, y) \geq \frac{1}{2} \|y\|_{\mathfrak{g}_{CM}} \text{ for all } y \in B_\varepsilon.$$

If in the above argument  $y$  was not in  $B_\varepsilon$ , then the path  $g$  would have had to exit  $B_\varepsilon$  and we could conclude that  $\ell_{G_{CM}}(g) \geq \|g(T)\|_{\mathfrak{g}_{CM}}/2 = \varepsilon/2$  and therefore that  $d_{G_{CM}}(\mathbf{e}, y) \geq \varepsilon/2$ . Hence we have shown that

$$\|y\| = d_{G_{CM}}(\mathbf{e}, y) \geq \frac{1}{2} \min\left(\varepsilon, \|y\|_{\mathfrak{g}_{CM}}\right) \text{ for all } y \in G_{CM}.$$

Now suppose that  $x, y \in G_{CM}$  and (without loss of generality) that  $\|x\|_{\mathfrak{g}_{CM}} \leq \|y\|_{\mathfrak{g}_{CM}}$ . Using the left invariance of  $d_{G_{CM}}$ , it follows that

$$(3.23) \quad d_{G_{CM}}(x, y) = d_{G_{CM}}(\mathbf{e}, x^{-1}y) \geq \frac{1}{2} \min\left(\varepsilon, \|x^{-1}y\|_{\mathfrak{g}_{CM}}\right).$$

If we further suppose that  $d_{G_{CM}}(x, y) < \frac{\varepsilon}{2}$ , we may conclude from Equation (3.23) that

$$\left\| y - x - \frac{1}{2}[x, y] \right\|_{\mathfrak{g}_{CM}} = \|x^{-1}y\|_{\mathfrak{g}_{CM}} \leq 2d_{G_{CM}}(x, y).$$

If we write  $x = (A, a)$  and  $y = (B, b)$ , it follows that

$$\|B - A\|_H^2 + \left\| b - a - \frac{1}{2}\omega(A, B) \right\|_{\mathbf{C}}^2 \leq 4d_{G_{CM}}^2(x, y)$$

and therefore  $\|B - A\|_H \leq 2d_{G_{CM}}(x, y)$  and

$$\begin{aligned} \|b - a\|_{\mathbf{C}} &\leq \left\| b - a - \frac{1}{2}\omega(A, B) \right\|_{\mathbf{C}} + \left\| \frac{1}{2}\omega(A, B) \right\|_{\mathbf{C}} \\ &\leq 2d_{G_{CM}}(x, y) + \frac{1}{2} \|\omega(A, B - A)\|_{\mathbf{C}} \\ &\leq 2d_{G_{CM}}(x, y) + \frac{C}{2} \|A\|_H \|B - A\|_H \\ &\leq 2d_{G_{CM}}(x, y) \left(1 + \frac{C}{2} \|A\|_H\right) \leq 2d_{G_{CM}}(x, y) \left(1 + \frac{C}{2} \|x\|_{\mathfrak{g}_{CM}}\right). \end{aligned}$$

Combining these results shows that if  $d_{G_{CM}}(x, y) < \frac{\varepsilon}{2}$  then

$$\|y - x\|_{\mathfrak{g}_{CM}}^2 \leq 4d_{G_{CM}}^2(x, y) \left( 1 + \left( 1 + \frac{C}{2} \|x\|_{\mathfrak{g}_{CM}} \right)^2 \right)$$

from which Equation (3.19) easily follows.  $\square$

We are most interested in the case where  $\{\omega(A, B) : A, B \in H\}$  is a total subset of  $\mathbf{C}$ , i.e.  $\text{span}\{\omega(A, B) : A, B \in H\} = \mathbf{C}$ . In this case it turns out that straight line paths are bad approximations to the geodesics joining  $\mathbf{e} \in G_{CM}$  to points  $x \in G_{CM}$  far away from  $\mathbf{e}$ . For points  $x \in G_{CM}$  distant from  $\mathbf{e}$  it is better to use “horizontal” paths instead which leads to the following distance estimates.

**Theorem 3.12.** *Suppose that  $\{\omega(A, B) : A, B \in H\}$  is a total subset of  $\mathbf{C}$ . Then there exists  $C(\omega) < \infty$  such that*

$$(3.24) \quad d_{CM}(\mathbf{e}, (A, a)) \leq C(\omega) \left( \|A\|_H + \sqrt{\|a\|_{\mathbf{C}}} \right) \text{ for all } (A, a) \in \mathfrak{g}_{CM}.$$

Moreover, for any  $\varepsilon_0 > 0$  there exists  $\gamma(\varepsilon_0) > 0$  such that and

$$(3.25) \quad \gamma(\varepsilon_0) \left( \|A\|_H + \sqrt{\|a\|_{\mathbf{C}}} \right) \leq d_{CM}(\mathbf{e}, (A, a)) \text{ if } d_{CM}(\mathbf{e}, (A, a)) \geq \varepsilon_0.$$

Thus away from any neighborhood of the identity,  $d_{CM}(\mathbf{e}, (A, a))$  is comparable to  $\|A\|_H + \sqrt{\|a\|_{\mathbf{C}}}$ .

Since this theorem is not central to the rest of the paper we will relegate its proof to Appendix C. The main point of Theorem 3.12 is to explain why Theorem 4.16 is an infinite dimensional analogue of the integrated Gaussian heat kernel bound in Eq. (1.5).

### 3.2. Norm estimates.

**Notation 3.13.** *Suppose  $H$  and  $\mathbf{C}$  are real (complex) Hilbert spaces,  $L : H \rightarrow \mathbf{C}$  is a bounded operator,  $\omega : H \times H \rightarrow \mathbf{C}$  is a continuous (complex) bilinear form, and  $\{e_j\}_{j=1}^{\infty}$  is an orthonormal basis for  $H$ . The Hilbert–Schmidt norms of  $L$  and  $\omega$  are defined by*

$$(3.26) \quad \|L\|_{H^* \otimes \mathbf{C}}^2 := \sum_{j=1}^{\infty} \|Le_j\|_{\mathbf{C}}^2,$$

and

$$(3.27) \quad \|\omega\|_2^2 = \|\omega\|_{H^* \otimes H^* \otimes \mathbf{C}}^2 := \sum_{i,j=1}^{\infty} \|\omega(e_i, e_j)\|_{\mathbf{C}}^2.$$

It is easy to verify directly that these definitions are basis independent. Also see Equation (3.29) below.

**Proposition 3.14.** *Suppose that  $(W, H, \mu)$  is a real abstract Wiener space,  $\omega : W \times W \rightarrow \mathbf{C}$  is as in Notation 3.1, and  $\{e_j\}_{j=1}^{\infty}$  is an orthonormal basis for  $H$ . Then*

$$(3.28) \quad \|\omega(w, \cdot)\|_{H^* \otimes \mathbf{C}}^2 \leq C_2 \|\omega\|_0^2 \|w\|_W^2 \text{ for all } w \in W$$

and

$$(3.29) \quad \|\omega\|_2^2 = \int_{W \times W} \|\omega(w, w')\|_{\mathbf{C}}^2 d\mu(w) d\mu(w') \leq \|\omega\|_0^2 C_2^2 < \infty,$$

where  $C_2$  is as in Equation (2.2).

*Proof.* From Equation (2.13),

$$\begin{aligned} \|\omega(w, \cdot)\|_{H^* \otimes \mathbf{C}}^2 &= \int_W \|\omega(w, w')\|_{\mathbf{C}}^2 d\mu(w') \\ &\leq \|\omega\|_0^2 \|w\|_W^2 \int_W \|w'\|_W^2 d\mu(w') = C_2 \|\omega\|_0^2 \|w\|_W^2. \end{aligned}$$

Similarly, viewing  $w \rightarrow \omega(w, \cdot)$  as a continuous linear map from  $W$  to  $H^* \otimes \mathbf{C}$  it follows from Eqs. (2.13) and (2.14), that

$$\begin{aligned} \|\omega\|_2^2 &= \|h \mapsto \omega(h, \cdot)\|_{H^* \otimes (H^* \otimes \mathbf{C})}^2 = \int_W \|\omega(w, \cdot)\|_{H^* \otimes \mathbf{C}}^2 d\mu(w) \\ &\leq \int_W C_2 \|\omega\|_0^2 \|w\|_W^2 d\mu(w) = C_2^2 \|\omega\|_0^2. \end{aligned}$$

□

**Remark 3.15.** The Lie bracket on  $\mathfrak{g}_{CM}$  has the following continuity property,

$$\|[(A, a), (B, b)]\|_{\mathfrak{g}_{CM}} \leq C \|(A, a)\|_{\mathfrak{g}_{CM}} \|(B, b)\|_{\mathfrak{g}_{CM}}$$

where  $C \leq \|\omega\|_2$  as in Eq. (3.17). This is a consequence of the following simple estimates

$$\begin{aligned} \|[(A, a), (B, b)]\|_{\mathfrak{g}_{CM}} &= \|(0, \omega(A, B))\|_{\mathfrak{g}_{CM}} = \|\omega(A, B)\|_{\mathbf{C}} \\ &\leq C \|A\|_H \|B\|_H \leq C \|(A, a)\|_{\mathfrak{g}_{CM}} \|(B, b)\|_{\mathfrak{g}_{CM}}. \end{aligned}$$

This continuity property of the Lie bracket is often used to prove that the exponential map is a local diffeomorphism (e.g. see [24] in the case of infinite-dimensional matrix groups). In the Heisenberg group setting the exponential map is a global diffeomorphism as follows from Lemma 3.8, where we have not used continuity of the Lie bracket.

**Lemma 3.16.** *Suppose that  $H$  is a real Hilbert space,  $\mathbf{C}$  is a real finite-dimensional inner product space, and  $\ell : H \rightarrow \mathbf{C}$  is a continuous linear map. Then for any orthonormal basis  $\{e_j\}_{j=1}^\infty$  of  $H$  the series*

$$(3.30) \quad \sum_{j=1}^{\infty} \ell(e_j) \otimes \ell(e_j) \in \mathbf{C} \otimes \mathbf{C}$$

and

$$(3.31) \quad \sum_{j=1}^{\infty} \ell(e_j) \otimes e_j \in \mathbf{C} \otimes H$$

are convergent and independent of the basis.<sup>1</sup>

<sup>1</sup>If we were to allow  $\mathbf{C}$  to be an infinite-dimensional Hilbert space here, we would have to assume that  $\ell$  is Hilbert–Schmidt. When  $\dim \mathbf{C} < \infty$ ,  $\ell : H \rightarrow \mathbf{C}$  is Hilbert–Schmidt iff it is bounded.

*Proof.* If  $\{f_i\}_{i=1}^{\dim \mathbf{C}}$  is an orthonormal basis for  $\mathbf{C}$ , then

$$\begin{aligned} \sum_{j=1}^{\infty} \|\ell(e_j) \otimes \ell(e_j)\|_{\mathbf{C} \otimes \mathbf{C}} &= \sum_{j=1}^{\infty} \|\ell(e_j)\|_{\mathbf{C}}^2 \\ &= \sum_{i=1}^{\dim \mathbf{C}} \sum_{j=1}^{\infty} (f_i, \ell(e_j))^2 = \sum_{i=1}^{\dim \mathbf{C}} \|(f_i, \ell(\cdot))\|_{H^*}^2 < \infty \end{aligned}$$

which shows that the sum in Equation (3.30) is absolutely convergent and that  $\ell$  is Hilbert–Schmidt. Similarly, since  $\{\ell(e_j) \otimes e_j\}_{j=1}^{\infty}$  is an orthogonal set in  $\mathbf{C} \otimes H$  and

$$\sum_{j=1}^{\infty} \|\ell(e_j) \otimes e_j\|_{\mathbf{C} \otimes H}^2 = \sum_{j=1}^{\infty} \|\ell(e_j)\|_{\mathbf{C}}^2 < \infty,$$

the sum in Equation (3.31) is convergent as well.

Recall that if  $H$  and  $K$  are two real Hilbert spaces then the Hilbert space tensor product,  $H \otimes K$ , is unitarily equivalent to the space of Hilbert–Schmidt operators,  $HS(H, K)$ , from  $H$  to  $K$ . Under this identification,  $h \otimes k \in H \otimes K$  corresponds to the operator (still denoted by  $h \otimes k$ ) in  $HS(H, K)$  defined by;  $H \ni h' \rightarrow (h, h')_H k \in K$ . Using this identification we have that for all  $c \in \mathbf{C}$ ;

$$\begin{aligned} \left( \sum_{j=1}^{\infty} \ell(e_j) \otimes \ell(e_j) \right) c &= \sum_{j=1}^{\infty} \ell(e_j) \langle \ell(e_j), c \rangle_{\mathbf{C}} = \sum_{j=1}^{\infty} \ell(e_j) \langle e_j, \ell^* c \rangle_{\mathbf{C}} \\ &= \ell \left( \sum_{j=1}^{\infty} \langle e_j, \ell^* c \rangle_{\mathbf{C}} e_j \right) = \ell \ell^* c \end{aligned}$$

and

$$\left( \sum_{j=1}^{\infty} \ell(e_j) \otimes e_j \right) c = \sum_{j=1}^{\infty} e_j \langle \ell(e_j), c \rangle_{\mathbf{C}} = \sum_{j=1}^{\infty} e_j \langle e_j, \ell^* c \rangle_{\mathbf{C}} = \ell^* c,$$

which clearly shows that Equations (3.30) and (3.31) are basis-independent.  $\square$

**3.3. Examples.** Here we describe several examples including finite-dimensional Heisenberg groups. As we mentioned earlier a typical example of such a group is the Heisenberg group of a symplectic vector space. For each of the examples presented we will explicitly compute the norm  $\|\omega\|_2^2$  of the form  $\omega$  as defined in Equation (3.27). In Section 7 we will also explicitly compute the Ricci tensor for each of the examples introduced here.

To describe some of the examples below, it is convenient to use complex Banach and Hilbert spaces. However, for the purposes of this paper the complex structure on these spaces should be forgotten. In doing so we will use the following notation. If  $X$  is a complex vector space, let  $X_{\text{Re}}$  denote  $X$  thought of as a real vector space. If  $(H, \langle \cdot, \cdot \rangle_H)$  is a complex Hilbert space, we define  $\langle \cdot, \cdot \rangle_{H_{\text{Re}}} = \text{Re} \langle \cdot, \cdot \rangle_H$  in which case  $(H_{\text{Re}}, \langle \cdot, \cdot \rangle_{H_{\text{Re}}})$  becomes a real Hilbert space. Before going to the examples, let us record the relationship between the complex and real Hilbert-Schmidt norms of Notation 3.13.

**Lemma 3.17.** *Suppose  $H$  and  $\mathbf{C}$  are complex Hilbert spaces,  $L : H \rightarrow \mathbf{C}$  and  $\omega : H \times H \rightarrow \mathbf{C}$  are as in Notation 3.13, and  $c \in \mathbf{C}$ . Then*

$$(3.32) \quad \|L\|_{H_{\mathbb{R}e}^* \otimes \mathbf{C}_{\mathbb{R}e}}^2 = 2 \|L\|_{H^* \otimes \mathbf{C}}^2,$$

$$(3.33) \quad \|\langle \omega(\cdot, \cdot), c \rangle_{\mathbf{C}_{\mathbb{R}e}}\|_{H_{\mathbb{R}e}^* \otimes H_{\mathbb{R}e}^*}^2 = 2 \|\langle \omega(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_{H^* \otimes H^*}^2,$$

and

$$(3.34) \quad \|\omega(\cdot, \cdot)\|_{H_{\mathbb{R}e}^* \otimes H_{\mathbb{R}e}^* \otimes \mathbf{C}_{\mathbb{R}e}}^2 = 4 \|\omega(\cdot, \cdot)\|_{H^* \otimes H^* \otimes \mathbf{C}}^2.$$

*Proof.* A straightforward proof.  $\square$

**Example 3.18** (Finite-dimensional real Heisenberg group). *Let  $\mathbf{C} = \mathbb{R}$ ,  $W = H = (\mathbb{C}^n)_{\mathbb{R}e} \cong \mathbb{R}^{2n}$ , and  $\omega(w, z) := \text{Im} \langle w, z \rangle$  be the standard symplectic form on  $\mathbb{R}^{2n}$ , where  $\langle w, z \rangle = w \cdot \bar{z}$  is the usual inner product on  $\mathbb{C}^n$ . Any element of the group  $\mathbf{H}_{\mathbb{R}}^n := G(\omega)$  can be written as  $g = (z, c)$ , where  $z \in \mathbb{C}^n$  and  $c \in \mathbb{R}$ . As above, the Lie algebra,  $\mathfrak{h}_{\mathbb{R}}^n$ , of  $\mathbf{H}_{\mathbb{R}}^n$  is, as a set, equal to  $\mathbf{H}_{\mathbb{R}}^n$  itself. If  $\{e_j\}_{j=1}^n$  is an orthonormal basis for  $\mathbb{R}^n$  then  $\{e_j, ie_j\}_{j=1}^n$  is an orthonormal basis for  $H$  and (real) Hilbert-Schmidt norm of  $\omega$  is given by*

$$(3.35) \quad \|\omega\|_{H^* \otimes H^*}^2 = \sum_{j,k=1}^n \sum_{\varepsilon, \delta \in \{1, i\}} [\text{Im} \langle \varepsilon e_j, \delta e_k \rangle]^2 = \sum_{j,k=1}^n 2\delta_{j,k} = 2n.$$

**Example 3.19** (Finite-dimensional complex Heisenberg group). *Suppose that  $W = H = \mathbb{C}^n \times \mathbb{C}^n$ ,  $\mathbf{C} = \mathbb{C}$ , and  $\omega : W \times W \rightarrow \mathbb{C}$  is defined by*

$$\omega((w_1, w_2), (z_1, z_2)) = w_1 \cdot z_2 - w_2 \cdot z_1.$$

*Any element of the group  $\mathbf{H}_{\mathbb{C}}^n := G(\omega)$  can be written as  $g = (z_1, z_2, c)$ , where  $z_1, z_2 \in \mathbb{C}^n$  and  $c \in \mathbb{C}$ . As above, the Lie algebra,  $\mathfrak{h}_{\mathbb{C}}^n$ , of  $\mathbf{H}_{\mathbb{C}}^n$  is, as a set, equal to  $\mathbf{H}_{\mathbb{C}}^n$  itself. In this case  $\{(e_j, 0), (0, e_j)\}_{j=1}^n$  is a complex orthonormal basis for  $H$ . The (complex) Hilbert-Schmidt norm of the symplectic form  $\omega$  is given by*

$$\|\omega\|_{H^* \otimes H^*}^2 = 2 \sum_{j=1}^n |\omega((e_j, 0), (0, e_j))|^2 = 2n.$$

**Example 3.20.** *Let  $(K, \langle \cdot, \cdot \rangle)$  be a complex Hilbert space and  $Q$  be a strictly positive trace class operator on  $K$ . For  $h, k \in K$ , let  $\langle h, k \rangle_Q := \langle h, Qk \rangle$  and  $\|h\|_Q := \sqrt{\langle h, h \rangle_Q}$ . Also let  $(K_Q, \langle \cdot, \cdot \rangle_Q)$  denote the Hilbert space completion of  $(K, \|\cdot\|_Q)$ . Analogous to Example 3.18, let  $H := K_{\mathbb{R}e}$ ,  $W := (K_Q)_{\mathbb{R}e}$ , and  $\omega : W \times W \rightarrow \mathbb{R} =: \mathbf{C}$  be defined by*

$$\omega(w, z) = \text{Im} \langle w, z \rangle_Q \text{ for all } w, z \in W.$$

*Then  $G(\omega) = W \times \mathbb{R}$  is a real group and  $(W, H)$  determines an abstract Wiener space (see for example [36, Exercise 17, p. 59] and [8, Example 3.9.7]). Let  $\{e_j\}_{j=1}^{\infty}$  be an orthonormal basis for  $K$  so that  $\{e_j, ie_j\}_{j=1}^{\infty}$  is an orthonormal basis for  $(H, \text{Re} \langle \cdot, \cdot \rangle_K)$ . Then the real Hilbert-Schmidt norm of  $\omega$  is given by*

$$\|\omega\|_{H^* \otimes H^*}^2 = \sum_{j,k=1}^{\infty} \sum_{\varepsilon, \delta \in \{1, i\}} [\text{Im}^2 \langle \varepsilon e_j, Q\delta e_k \rangle]$$

$$\begin{aligned}
&= 2 \sum_{j,k=1}^{\infty} [\operatorname{Im}^2 \langle e_j, Qe_k \rangle + \operatorname{Re}^2 \langle e_j, Qe_k \rangle] = 2 \sum_{j,k=1}^{\infty} |\langle e_j, Qe_k \rangle|^2 \\
(3.36) \quad &= 2 \sum_{k=1}^{\infty} \|Qe_k\|^2 = 2 \|Q\|_{HS}^2 = 2 \operatorname{tr} Q^2.
\end{aligned}$$

**Example 3.21.** Again let  $(K, \langle \cdot, \cdot \rangle)$ ,  $Q$ , and  $(K_Q, \langle \cdot, \cdot \rangle_Q)$  be as in the previous example. Let us further assume that  $K$  is equipped with a conjugation,  $k \rightarrow \bar{k}$ , which is isometric and commutes with  $Q$ . Analogously to Example 3.19, let  $W := K_Q \times K_Q$ ,  $H = K \times K$ , and let  $\omega : W \times W \rightarrow \mathbb{C}$  be defined by

$$\omega((w_1, w_2), (z_1, z_2)) = \langle w_1, \bar{z}_2 \rangle_Q - \langle w_2, \bar{z}_1 \rangle_Q,$$

which is skew symmetric because the conjugation commutes with  $Q$ . If  $\{e_j\}_{j=1}^{\infty}$  is an orthonormal basis for  $K$ , then  $\{\bar{e}_j\}_{j=1}^{\infty}$  is also an orthonormal basis for  $K$  (because the conjugation is isometric) and  $\{(e_j, 0), (0, e_j)\}_{j=1}^{\infty}$  is a orthonormal basis for  $H$ . Hence, the (complex) Hilbert-Schmidt norm of  $\omega$  is given by

$$\begin{aligned}
\|\omega\|_{H^* \otimes H^*}^2 &= \sum_{j,k=1}^{\infty} (|\omega((e_j, 0), (0, e_k))|^2 + |\omega((0, e_k), (e_j, 0))|^2) \\
(3.37) \quad &= 2 \sum_{j,k=1}^{\infty} |\langle e_j, Q\bar{e}_k \rangle|^2 = 2 \sum_{k=1}^{\infty} \|Q\bar{e}_k\|^2 = 2 \|Q\|_{HS}^2 = 2 \operatorname{tr} Q^2.
\end{aligned}$$

**Example 3.22.** Suppose that  $(V, \langle \cdot, \cdot \rangle_V)$  is a  $d$ -dimensional  $\mathbb{F}$ -inner product space ( $\mathbb{F} = \mathbb{R}$  or  $\mathbb{C}$ ),  $\mathbf{C}$  is a finite-dimensional  $\mathbb{F}$ -inner product space,  $\alpha : V \times V \rightarrow \mathbf{C}$  is an anti-symmetric bilinear form on  $V$ , and  $\{q_j\}_{j=1}^{\infty}$  is a sequence of positive numbers such that  $\sum_{j=1}^{\infty} q_j < \infty$ . Let

$$\begin{aligned}
W &= \left\{ v \in V^{\mathbb{N}} : \sum_{j=1}^{\infty} q_j \|v_j\|_V^2 < \infty \right\} \text{ and} \\
H &= \left\{ v \in V^{\mathbb{N}} : \sum_{j=1}^{\infty} \|v_j\|_V^2 < \infty \right\} \subset W,
\end{aligned}$$

each of which are Hilbert spaces when equipped with the inner products

$$\begin{aligned}
\langle v, w \rangle_W &:= \sum_{j=1}^{\infty} q_j \langle v_j, w_j \rangle_V \text{ and} \\
\langle v, w \rangle_H &:= \sum_{j=1}^{\infty} \langle v_j, w_j \rangle_V
\end{aligned}$$

respectively. Further let  $\omega : W \times W \rightarrow \mathbf{C}$  be defined by

$$\omega(v, w) = \sum_{j=1}^{\infty} q_j \alpha(v_j, w_j).$$



Then  $(W_{\mathbb{R}e}, H_{\mathbb{R}e})$  is an abstract Wiener space (see for example [36, Exercise 17, p. 59] and [8, Example 3.9.7]) and, since

$$\begin{aligned} |\omega(v, w)| &= \sum_{j=1}^{\infty} q_j |\alpha(v_j, w_j)| \leq \|\alpha\|_0 \sum_{j=1}^{\infty} q_j \|v_j\|_V \|w_j\|_V \\ &\leq \|\alpha\|_0 \|v\|_W \|w\|_W, \end{aligned}$$

we have  $\|\omega\|_0 \leq \|\alpha\|_0$ . For  $v \in V$ , let  $v(j) := (0, \dots, 0, v, 0, 0, \dots) \in H$  where the  $v$  is put in the  $j^{\text{th}}$  - position. If  $\{u_a\}_{a=1}^d$  is an orthonormal basis for  $V$ , then  $\{u_a(j) : a = 1, \dots, d\}_{j=1}^{\infty}$  is an orthonormal basis for  $H$ . Therefore,

$$\begin{aligned} \|\langle \omega(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_{H^* \otimes H^*}^2 &= \sum_{j,k=1}^{\infty} \sum_{a,b=1}^d \langle \omega(u_a(j), u_b(k)), c \rangle_{\mathbf{C}}^2 \\ &= \sum_{j=1}^{\infty} \sum_{a,b=1}^d q_j^2 \langle \alpha(u_a, u_b), c \rangle_{\mathbf{C}}^2 \\ (3.38) \quad &= \left( \sum_{j=1}^{\infty} q_j^2 \right) \|\langle \omega(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_{V^* \otimes V^*}^2 \text{ for all } c \in \mathbf{C}. \end{aligned}$$

**Example 3.23.** Let  $(V, \langle \cdot, \cdot \rangle, \alpha)$  be as in Example 3.22 with  $\mathbb{F} = \mathbf{C}$ ,

$$W = \{\sigma \in C([0, 1], V) : \sigma(0) = 0\}$$

and  $H$  be the associated Cameron - Martin space,

$$H := H(V) = \left\{ h \in W : \int_0^1 \|h'(s)\|_V^2 ds < \infty \right\},$$

wherein  $\int_0^1 \|h'(s)\|_V^2 ds := \infty$  if  $h$  is not absolutely continuous. Further let  $\eta$  be a complex measure on  $[0, 1]$  and

$$\omega(\sigma_1, \sigma_2) := \int_0^1 \alpha(\sigma_1(s), \sigma_2(s)) d\eta(s) \text{ for all } \sigma_1, \sigma_2 \in W.$$

Then  $(W, H, \omega)$  satisfies all of the assumptions in Notation 3.1. Let  $\{u_a\}_{a=1}^d$  be the orthonormal basis of  $V$ ,  $\{l_j\}_{j=1}^{\infty}$  be the orthonormal basis of  $H(\mathbb{R})$ , then  $\{l_j u_a : a = 1, 2, \dots, d\}_{j=1}^{\infty}$  is an orthonormal basis of  $H$  and (see [22, Lemma 3.8])

$$(3.39) \quad \sum_{j=1}^{\infty} l_j(s) l_j(t) = s \wedge t \text{ for all } s, t \in [0, 1].$$

If we let  $\lambda$  be the total variation of  $\eta$ , then  $d\eta = \rho d\lambda$ , where  $\rho = \frac{d\eta}{d\lambda}$ . Hence if  $d\bar{\eta}(t) := \bar{\rho}(t) d\lambda(t)$  and  $c \in \mathbf{C}$ , then

$$\begin{aligned} &\|\langle \omega(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_2^2 \\ &= \sum_{j,k=1}^{\infty} \sum_{a,b=1}^d |\langle \omega(l_j u_a, l_k u_b), c \rangle_{\mathbf{C}}|^2 \\ &= \sum_{j,k=1}^{\infty} \sum_{a,b=1}^d \left| \int_{[0,1]} l_j(s) l_k(s) \rho(s) d\lambda(s) \langle \alpha(u_a, u_b), c \rangle_{\mathbf{C}} \right|^2 \end{aligned}$$

$$\begin{aligned}
&= \|\langle \alpha(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_2^2 \cdot \sum_{j,k=1}^{\infty} \int_{[0,1]^2} l_j(s) l_k(s) l_j(t) l_k(t) \rho(s) \bar{\rho}(t) d\lambda(s) d\lambda(t) \\
&= \|\langle \alpha(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_2^2 \cdot \int_{[0,1]^2} (s \wedge t)^2 \rho(s) \bar{\rho}(t) d\lambda(s) d\lambda(t) \\
(3.40) \quad &= \|\langle \alpha(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_2^2 \cdot \int_{[0,1]^2} (s \wedge t)^2 d\eta(s) d\bar{\eta}(t),
\end{aligned}$$

wherein we have used Equation (3.39) in the fourth equality above. Summing this equation over  $c$  in an orthonormal basis for  $\mathbf{C}$  shows

$$(3.41) \quad \|\omega\|_2^2 = \|\alpha\|_2^2 \cdot \int_{[0,1]^2} (s \wedge t)^2 d\eta(s) d\bar{\eta}(t).$$

**3.4. Finite Dimensional Projections and Cylinder Functions.** Let  $i : H \rightarrow W$  be the inclusion map, and  $i^* : W^* \rightarrow H^*$  be its transpose, i.e.  $i^*\ell := \ell \circ i$  for all  $\ell \in W^*$ . Also let

$$H_* := \{h \in H : \langle \cdot, h \rangle_H \in \text{Ran}(i^*) \subset H^*\}$$

or in other words,  $h \in H$  is in  $H_*$  iff  $\langle \cdot, h \rangle_H \in H^*$  extends to a continuous linear functional on  $W$ . (We will continue to denote the continuous extension of  $\langle \cdot, h \rangle_H$  to  $W$  by  $\langle \cdot, h \rangle_H$ .) Because  $H$  is a dense subspace of  $W$ ,  $i^*$  is injective and because  $i$  is injective,  $i^*$  has a dense range. Since  $h \mapsto \langle \cdot, h \rangle_H$  as a map from  $H$  to  $H^*$  is a conjugate linear isometric isomorphism, it follows from the above comments that  $H_* \ni h \rightarrow \langle \cdot, h \rangle_H \in W^*$  is a conjugate linear isomorphism too, and that  $H_*$  is a dense subspace of  $H$ .

Now suppose that  $P : H \rightarrow H$  is a finite rank orthogonal projection such that  $PH \subset H_*$ . Let  $\{e_j\}_{j=1}^n$  be an orthonormal basis for  $PH$  and  $\ell_j = \langle \cdot, e_j \rangle_H \in W^*$ . Then we may extend  $P$  to a (unique) continuous operator from  $W \rightarrow H$  (still denoted by  $P$ ) by letting

$$(3.42) \quad Pw := \sum_{j=1}^n \langle w, e_j \rangle_H e_j = \sum_{j=1}^n \ell_j(w) e_j \text{ for all } w \in W.$$

For all  $w \in W$  we have,  $\|Pw\|_H \leq C_2(P) \|Pw\|_W$  and

$$\|Pw\|_W \leq \left( \sum_{i=1}^n \|\langle \cdot, e_i \rangle_H\|_W \|e_i\|_W \right) \|w\|_W$$

and therefore there exists  $C < \infty$  such that

$$(3.43) \quad \|Pw\|_H \leq C \|w\|_W \text{ for all } w \in W.$$

**Notation 3.24.** Let  $\text{Proj}(W)$  denote the collection of finite rank projections on  $W$  such that  $PW \subset H_*$  and  $P|_H : H \rightarrow H$  is an orthogonal projection, i.e.  $P$  has the form given in Equation (3.42). Further, let  $G_P := PW \times \mathbf{C}$  (a subgroup of  $G_{CM}$ ) and

$$\pi = \pi_P : G \rightarrow G_P$$

be defined by  $\pi_P(w, c) := (Pw, c)$ .

**Remark 3.25.** The reader should be aware that  $\pi_P : G \rightarrow G_P \subset G_{CM}$  is **not** (for general  $\omega$  and  $P \in \text{Proj}(W)$ ) a group homomorphism. In fact we have,

$$(3.44) \quad \pi_P [(w, c) \cdot (w', c')] - \pi_P (w, c) \cdot \pi_P (w', c') = \Gamma_P (w, w'),$$

where

$$(3.45) \quad \Gamma_P (w, w') = \frac{1}{2} (0, \omega (w, w') - \omega (Pw, Pw')).$$

So unless  $\omega$  is “supported” on the range of  $P$ ,  $\pi_P$  is not a group homomorphism. Since,  $(w, b) + (0, c) = (w, b) \cdot (0, c)$  for all  $w \in W$  and  $b, c \in \mathbf{C}$ , we may also write Equation 3.44 as

$$(3.46) \quad \pi_P [(w, c) \cdot (w', c')] = \pi_P (w, c) \cdot \pi_P (w', c') \cdot \Gamma_P (w, w').$$

**Definition 3.26.** A function  $f : G \rightarrow \mathbf{C}$  is said to be a **(smooth) cylinder function** if it may be written as  $f = F \circ \pi_P$  for some  $P \in \text{Proj}(W)$  and some (smooth) function  $F : G_P \rightarrow \mathbf{C}$ .

**Notation 3.27.** For  $g = (w, c) \in G$ , let  $\gamma(g)$  and  $\chi(g)$  be the elements of  $\mathfrak{g}_{CM} \otimes \mathfrak{g}_{CM}$  defined by

$$\begin{aligned} \gamma(g) &:= \sum_{j=1}^{\infty} (0, \omega (w, e_j)) \otimes (e_j, 0) \text{ and} \\ \chi(g) &:= \sum_{j=1}^{\infty} (0, \omega (w, e_j)) \otimes (0, \omega (w, e_j)) \end{aligned}$$

where  $\{e_j\}_{j=1}^{\infty}$  is any orthonormal basis for  $H$ . Both  $\gamma$  and  $\chi$  are well defined because of Lemma 3.16.

**Notation 3.28** (Left differentials). Suppose  $f : G \rightarrow \mathbf{C}$  is a smooth cylinder function. For  $g \in G$  and  $h, h_1, \dots, h_n \in \mathfrak{g}$ ,  $n \in \mathbb{N}$  let

$$(3.47) \quad \begin{aligned} (D^0 f)(g) &= f(g) \text{ and} \\ (D^n f)(g)(h_1 \otimes \dots \otimes h_n) &= \tilde{h}_1 \dots \tilde{h}_n f(g), \end{aligned}$$

where  $\tilde{h}f$  is given as in Equation (3.10) or Equation (3.12). We will write  $Df$  for  $D^1 f$ .

**Proposition 3.29.** Let  $\{e_j\}_{j=1}^{\infty}$  and  $\{f_\ell\}_{\ell=1}^d$  be orthonormal bases for  $H$  and  $\mathbf{C}$  respectively. Then for any smooth cylinder function,  $f : G \rightarrow \mathbf{C}$ ,

$$(3.48) \quad Lf(g) := \sum_{j=1}^{\infty} \left[ \widetilde{(e_j, 0)}^2 f \right] (g) + \sum_{\ell=1}^d \left[ \widetilde{(0, f_\ell)}^2 f \right] (g)$$

is well defined. Moreover, if  $f = F \circ \pi_P$ ,  $\partial_h$  is as in Notation 3.5 for all  $h \in \mathfrak{g}_{CM}$ ,

$$(3.49) \quad \Delta_H f(g) := \sum_{j=1}^{\infty} \partial_{(e_j, 0)}^2 f(g) = (\Delta_{PH} F)(Pw, c)$$

and

$$(3.50) \quad \Delta_{\mathbf{C}} f(g) := \sum_{\ell=1}^d \left[ \partial_{(0, f_\ell)}^2 f \right] (g) = (\Delta_{\mathbf{C}} F)(Pw, c),$$

then

$$(3.51) \quad Lf(g) = (\Delta_H f + \Delta_{\mathbf{C}} f)(g) + f''(g) \left( \gamma(g) + \frac{1}{4} \chi(g) \right).$$

*Proof.* The proof of the second equality in Eq. (3.49) is straightforward and will be left to the reader. Recall from Equation (3.12) that

$$(3.52) \quad \widetilde{(e_j, 0)} f(g) = f'(g) \left( e_j, \frac{1}{2} \omega(w, e_j) \right).$$

Applying  $\widetilde{(e_j, 0)}$  to both sides of Equation (3.52) gives

$$(3.53) \quad \widetilde{(e_j, 0)}^2 f(g) = f''(g) \left( \left( e_j, \frac{1}{2} \omega(w, e_j) \right) \otimes \left( e_j, \frac{1}{2} \omega(w, e_j) \right) \right) \\ = f''(g) \left( (e_j, 0) \otimes (e_j, 0) \right) + f''(g) \left( (0, \omega(w, e_j)) \otimes (e_j, 0) \right)$$

$$(3.54) \quad + \frac{1}{4} f''(g) \left( (0, \omega(w, e_j)) \otimes (0, \omega(w, e_j)) \right)$$

wherein we have used,

$$\partial_{e_j} \omega(\cdot, e_j) = \omega(e_j, e_j) = 0.$$

Summing Equation (3.54) on  $j$  shows,

$$\sum_{j=1}^{\infty} \left[ \widetilde{(e_j, 0)}^2 f \right](g) = \sum_{j=1}^{\infty} f''(g) \left( (e_j, 0) \otimes (e_j, 0) \right) + f''(g) \left( \gamma(g) + \frac{1}{4} \chi(g) \right) \\ = \sum_{j=1}^{\infty} \partial_{(e_j, 0)}^2 f(g) + f''(g) \left( \gamma(g) + \frac{1}{4} \chi(g) \right).$$

The formula in Equation (3.51) for  $Lf$  is now easily verified and this shows that  $Lf$  is independent of the choice of orthonormal bases for  $H$  and  $\mathbf{C}$  appearing in Equation (3.48).  $\square$

#### 4. BROWNIAN MOTION AND HEAT KERNEL MEASURES

For the Hilbert space stochastic calculus background needed for this section, see Métivier [41]. For the background on Itô integral relative to an abstract Wiener space-valued Brownian motion, see Kuo [36, pages 188-207] (especially Theorem 5.1), Kusuoka and Stroock [37, p. 5], and the appendix in [16].

Suppose now that  $(B(t), B_0(t))$  is a smooth curve in  $\mathfrak{g}_{CM}$  with  $(B(0), B_0(0)) = (0, 0)$  and consider solving, for  $g(t) = (w(t), c(t)) \in G_{CM}$ , the differential equation

$$(4.1) \quad (\dot{w}(t), \dot{c}(t)) = \dot{g}(t) = l_{g(t)*} \left( \dot{B}(t), \dot{B}_0(t) \right) \text{ with } g(0) = (0, 0).$$

By Equation (3.11), it follows that

$$(\dot{w}(t), \dot{c}(t)) = \left( \dot{B}(t), \dot{B}_0(t) + \frac{1}{2} \omega(w(t), \dot{B}(t)) \right)$$

and therefore the solution to Equation (4.1) is given by

$$(4.2) \quad g(t) = (w(t), c(t)) = \left( B(t), B_0(t) + \frac{1}{2} \int_0^t \omega(B(\tau), \dot{B}(\tau)) d\tau \right).$$

Below in subsection 4.2, we will replace  $B$  and  $B_0$  by Brownian motions and use this to define a Brownian motion on  $G$ .

4.1. **A quadratic integral.** Let  $\{(B(t), B_0(t))\}_{t \geq 0}$  be a **Brownian motion** on  $\mathfrak{g}$  with variance determined by

$$\begin{aligned} \mathbb{E} \left[ \langle (B(s), B_0(s)), (A, a) \rangle_{\mathfrak{g}_{CM}} \langle (B(t), B_0(t)), (C, c) \rangle_{\mathfrak{g}_{CM}} \right] \\ = \operatorname{Re} \langle (A, a), (C, c) \rangle_{\mathfrak{g}_{CM}} \min(s, t) \end{aligned}$$

for all  $s, t \in [0, \infty)$ ,  $A, C \in H_*$  and  $a, c \in \mathbf{C}$ . Also let  $\{e_j\}_{j=1}^\infty \subset H_*$  be an orthonormal basis for  $H$ . For  $n \in \mathbb{N}$ , define  $P_n \in \operatorname{Proj}(W)$  as in Notation 3.24, i.e.

$$(4.3) \quad P_n(w) = \sum_{j=1}^n \langle w, e_j \rangle_H e_j = \sum_{j=1}^n \ell_j(w) e_j \text{ for all } w \in W.$$

**Proposition 4.1.** *For each  $n$ , let  $M_t^n := \int_0^t \omega(B(\tau), dP_n B(\tau))$ . Then*

(1)  $\{M_t^n\}_{t \geq 0}$  is an  $L^2$ -martingale and there exists an  $L^2$ -martingale,  $\{M_t\}_{t \geq 0}$  with values in  $\mathbf{C}$  such that

$$(4.4) \quad \lim_{n \rightarrow \infty} \mathbb{E} \left[ \max_{t \leq T} \|M_t - M_t^n\|_{\mathbf{C}}^2 \right] = 0 \text{ for all } T < \infty.$$

(2) The quadratic variation of  $M$  is given by;

$$(4.5) \quad \langle M \rangle_t = \int_0^t \|\omega(B(\tau), \cdot)\|_{H^* \otimes \mathbf{C}}^2 d\tau.$$

(3) The square integrable martingale,  $M_t$ , is well defined independent of the choice of the orthonormal basis,  $\{e_j\}_{j=1}^\infty$  and hence will be denoted by  $\int_0^t \omega(B(\tau), dB(\tau))$ .

(4) For each  $p \in [1, \infty)$ ,  $\{M_t\}_{t \geq 0}$  is  $L^p$ -integrable and there exists  $c_p < \infty$  such that

$$\mathbb{E} \left( \sup_{0 \leq t \leq T} \|M_t\|_{\mathbf{C}}^p \right) \leq c_p T^p < \infty \text{ for all } 0 \leq T < \infty.$$

(This estimate will be considerably generalized in Proposition 4.13 below.)

*Proof.* 1. For  $P \in \operatorname{Proj}(W)$  let  $M_t^P := \int_0^t \omega(B(\tau), dP B(\tau))$ . Let  $P, Q \in \operatorname{Proj}(W)$  and choose an orthonormal basis,  $\{v_l\}_{l=1}^N$  for  $\operatorname{Ran}(P) + \operatorname{Ran}(Q)$ . We then have

$$(4.6) \quad \begin{aligned} \mathbb{E} \left[ \left\| M_T^P - M_T^Q \right\|_{\mathbf{C}}^2 \right] &= \mathbb{E} \int_0^T \sum_{l=1}^N \|\omega(B(\tau), (P-Q)v_l)\|_{\mathbf{C}}^2 d\tau \\ &= \mathbb{E} \int_0^T \sum_{l=1}^\infty \|\omega(B(\tau), (P-Q)e_l)\|_{\mathbf{C}}^2 d\tau \end{aligned}$$

$$(4.7) \quad \begin{aligned} &= \int_0^T \sum_{l=1}^\infty \sum_{k=1}^\infty \|\omega(e_k, (P-Q)e_l)\|_{\mathbf{C}}^2 \tau d\tau \\ &= \frac{T^2}{2} \sum_{l=1}^\infty \sum_{k=1}^\infty \|\omega(e_k, (P-Q)e_l)\|_{\mathbf{C}}^2. \end{aligned}$$

Taking  $P = P_n$  and  $Q = P_m$  with  $m \leq n$  in Eq. (4.7) allows us to conclude that

$$\mathbb{E} \left[ \left\| M_T^n - M_T^m \right\|_{\mathbf{C}}^2 \right] = \frac{T^2}{2} \sum_{j=m+1}^n \sum_{l=1}^\infty \|\omega(e_l, e_j)\|_{\mathbf{C}}^2 \rightarrow 0 \text{ as } m, n \rightarrow \infty$$

because  $\|\omega\|_2^2 < \infty$  by Proposition 3.14. Since the space of continuous  $L^2$ -martingales on  $[0, T]$  is complete in the norm,  $N \rightarrow \mathbb{E}\|N_T\|_{\mathbf{C}}^2$  and, by Doob's maximal inequality ([34, Proposition 7.16]), there exists  $c < \infty$  such that

$$\mathbb{E} \left[ \max_{t \leq T} \|N_t\|_{\mathbf{C}}^p \right] \leq c \mathbb{E} \|N_T\|_{\mathbf{C}}^p,$$

it follows that there exists a square integrable  $\mathbf{C}$ -valued martingale,  $\{M_t\}_{t \geq 0}$ , such that Eq. (4.4) holds.

2. Since the quadratic variation of  $M^n$  is given by

$$\langle M^n \rangle_t = \int_0^t \|\omega(B(\tau), dP_n B(\tau))\|_{\mathbf{C}}^2 = \int_0^t \sum_{l=1}^n \|\omega(B(\tau), e_l)\|_{\mathbf{C}}^2 d\tau$$

and

$$\begin{aligned} \mathbb{E} [|\langle M \rangle_t - \langle M^n \rangle_t|] &\leq \sqrt{\mathbb{E} [\langle M - M^n \rangle_t] \cdot \mathbb{E} [\langle M + M^n \rangle_t]} \\ &= \sqrt{\mathbb{E} \|M_t - M_t^n\|_{\mathbf{C}}^2 \cdot \mathbb{E} \|M_t + M_t^n\|_{\mathbf{C}}^2} \rightarrow 0 \text{ as } n \rightarrow \infty, \end{aligned}$$

Eq. (4.5) easily follows.

3. Suppose now that  $\{e'_j\}_{j=1}^\infty \subset H_*$  is another orthonormal basis for  $H$  and  $P'_n : W \rightarrow H_*$  are the corresponding orthogonal projections. Taking  $P = P_n$  and  $P' = P'_n$  in Eq. (4.7) gives,

$$(4.8) \quad \mathbb{E} \left\| M_T^{P_n} - M_T^{P'_n} \right\|_{\mathbf{C}}^2 = \frac{T^2}{2} \sum_{l=1}^{\infty} \sum_{k=1}^{\infty} \|\omega(e_k, (P_n - P'_n) e_l)\|_{\mathbf{C}}^2.$$

Since

$$\begin{aligned} \sum_{l=1}^{\infty} \sum_{k=1}^{\infty} \|\omega(e_k, P'_n e_l) - \omega(e_k, e_l)\|_{\mathbf{C}}^2 &= \sum_{l=1}^{\infty} \sum_{k=1}^{\infty} \|\omega(e_k, (P'_n - I) e_l)\|_{\mathbf{C}}^2 \\ &= \sum_{l=1}^{\infty} \sum_{k=1}^{\infty} \|\omega(e'_k, (P'_n - I) e'_l)\|_{\mathbf{C}}^2 \\ &= \sum_{l=n+1}^{\infty} \sum_{k=1}^{\infty} \|\omega(e'_k, e'_l)\|_{\mathbf{C}}^2 \rightarrow 0 \text{ as } n \rightarrow \infty \end{aligned}$$

and similarly but more easily,  $\sum_{l=1}^{\infty} \sum_{k=1}^{\infty} \|\omega(e_k, P_n e_l) - \omega(e_k, e_l)\|_{\mathbf{C}}^2 \rightarrow 0$  as  $n \rightarrow \infty$ , we may pass to the limit in Eq. (4.8) to learn that  $\lim_{n \rightarrow \infty} \mathbb{E} \left\| M_T^{P_n} - M_T^{P'_n} \right\|_{\mathbf{C}}^2 = 0$ .

4. By Jensen's inequality

$$\begin{aligned} \left( \int_0^T \|\omega(B(s), \cdot)\|_{H^* \otimes \mathbf{C}}^2 ds \right)^{p/2} &= T^{p/2} \left( \int_0^T \|\omega(B(s), \cdot)\|_{H^* \otimes \mathbf{C}}^2 \frac{ds}{T} \right)^{p/2} \\ &\leq T^{p/2} \int_0^T \|\omega(B(s), \cdot)\|_{H^* \otimes \mathbf{C}}^p \frac{ds}{T} \\ &= T^{\frac{p}{2}-1} \int_0^T \|\omega(B(s), \cdot)\|_{H^* \otimes \mathbf{C}}^p ds. \end{aligned}$$

Combining this estimate with Equation (3.28) and then applying either Skorohod's or Fernique's inequality (see Equations (2.3) or (2.4)) shows

$$\begin{aligned}
\mathbb{E} \left[ \langle M \rangle_T^{p/2} \right] &\leq T^{\frac{p}{2}-1} \int_0^T \mathbb{E} \|\omega(B(s), \cdot)\|_{H^* \otimes \mathbb{C}}^p ds \\
&\leq T^{\frac{p}{2}-1} \int_0^T C_2^{p/2} \|\omega\|_0^p \|B(s)\|_W^p ds \\
&\leq T^{\frac{p}{2}-1} C_2^{p/2} \|\omega\|_0^p \int_W \|y\|_W^p d\mu(y) \int_0^T s^{p/2} ds \\
(4.9) \qquad &= T^{\frac{p}{2}-1} C_2^{p/2} \|\omega\|_0^p C_p \frac{T^{p/2+1}}{p/2+1} = c'_p T^p.
\end{aligned}$$

As a consequence of the Burkholder-Davis-Gundy inequality (see for example [49, Corollary 6.3.1a on p.344], [45, Appendix A.2], or [41, p. 212] and [34, Theorem 17.7] for the real case), for any  $p \geq 2$  there exists  $c''_p < \infty$  such that

$$\mathbb{E} \left( \sup_{0 \leq t \leq T} \|M_t\|_{\mathbb{C}} \right)^p \leq c''_p \mathbb{E} \left[ \langle M \rangle_T^{p/2} \right] = c''_p c'_p T^p =: c_p T^p.$$

□

**4.2. Brownian Motion on  $G(\omega)$ .** Motivated by Eq. (4.2) we have the following definition.

**Definition 4.2.** Let  $(B(t), B_0(t))$  be a  $\mathfrak{g}$ -valued Brownian motion as in subsection 4.1. A **Brownian motion** on  $G$  is the continuous  $G$ -valued process defined by

$$(4.10) \qquad g(t) = \left( B(t), B_0(t) + \frac{1}{2} \int_0^t \omega(B(\tau), dB(\tau)) \right).$$

Further, for  $T > 0$ , let  $\nu_T = \text{Law}(g(T))$  be a probability measure on  $G$ . We refer to  $\nu_T$  as the **time  $T$  heat kernel measure on  $G$** .

**Remark 4.3.** An alert reader may complain that we should use the Stratonovich integral in Eq. (4.10) rather than the Itô integral. However, these two integrals are equal since  $\omega$  is a skew symmetric form

$$\begin{aligned}
\int_0^t \omega(B(\tau), \circ dB(\tau)) &= \int_0^t \omega(B(\tau), dB(\tau)) + \frac{1}{2} \int_0^t \omega(dB(\tau), dB(\tau)) \\
&= \int_0^t \omega(B(\tau), dB(\tau)).
\end{aligned}$$

**Theorem 4.4** (The generator of  $g(t)$ ). *The generator of  $g(t)$  is the operator  $L$  defined in Proposition 3.29. More precisely, if  $f : G \rightarrow \mathbb{C}$  is a smooth cylinder function, then*

$$(4.11) \qquad d[f(g(t))] = f'(g(t)) dg(t) + \frac{1}{2} Lf(g(t)) dt$$

where  $L$  is given in Proposition 3.29,  $f'$  is defined as in Notation 3.5 and

$$dg(t) = \left( dB(t), dB_0(t) + \frac{1}{2} \omega(B(t), dB(t)) \right).$$

*Proof.* Let us begin by observing that

$$\begin{aligned}
(4.12) \quad dg(t) \otimes dg(t) &= \left( dB(t), dB_0(t) + \frac{1}{2} \omega(B(t), dB(t)) \right)^{\otimes 2} \\
&= \left[ \left( dB(t), \frac{1}{2} \omega(B(t), dB(t)) \right) + (0, dB_0(t)) \right]^{\otimes 2} \\
&= \sum_{j=1}^{\infty} \left( e_j, \frac{1}{2} \omega(B(t), e_j) \right)^{\otimes 2} dt + \sum_{\ell=1}^d (0, f_\ell)^{\otimes 2} dt
\end{aligned}$$

where  $\{f_\ell\}_{\ell=1}^d$  is an orthonormal basis for  $\mathbf{C}$  and  $\{e_j\}_{j=1}^{\infty}$  is an orthonormal basis for  $H$ . Hence, as a consequence of Itô's formula, we have

$$\begin{aligned}
d[f(g(t))] &= f'(g(t)) dg(t) + \frac{1}{2} f''(g(t)) (dg(t) \otimes dg(t)) \\
&= f'(g(t)) dg(t) \\
&\quad + \frac{1}{2} f''(g(t)) \sum_{j=1}^{\infty} \left( e_j, \frac{1}{2} \omega(B(t), e_j) \right)^{\otimes 2} dt + \frac{1}{2} f''(g(t)) \sum_{\ell=1}^d (0, f_\ell)^{\otimes 2} dt \\
&= f'(g(t)) dg(t) + \frac{1}{2} \sum_{j=1}^{\infty} \left( \widetilde{(e_j, 0)^2} f \right) (g(t)) dt \\
&\quad + \frac{1}{2} \sum_{\ell=1}^d \left( \widetilde{(0, f_\ell)^2} f \right) (g(t)) dt \\
&= f'(g(t)) (dg(t)) + \frac{1}{2} Lf(g(t)) dt.
\end{aligned}$$

□

For the next corollary, let  $P \in \text{Proj}(W)$  as in Equation (3.42),  $F \in C^2(PH \times \mathbf{C}, \mathbb{C})$ , and  $f = F \circ \pi_P : G \rightarrow \mathbb{C}$  be a cylinder function where  $P \in \text{Proj}(W)$ . We will further suppose there exist  $0 < K, p < \infty$  such that

$$(4.13) \quad |F(h, c)| + \|F'(h, c)\| + \|F''(h, c)\| \leq K(1 + \|h\|_H + \|c\|_{\mathbf{C}})^p$$

for any  $h \in PH$  and  $c \in \mathbf{C}$ . Further let  $\{f_\ell\}_{\ell=1}^d$  be an orthonormal basis for  $\mathbf{C}$  and extend  $\{e_j\}_{j=1}^n$  to an orthonormal basis,  $\{e_j\}_{j=1}^{\infty}$ , for  $H$ .

**Corollary 4.5.** *If  $f : G \rightarrow \mathbb{C}$  is a cylinder function as above, then*

$$(4.14) \quad \mathbb{E}[f(g(T))] = f(\mathbf{e}) + \frac{1}{2} \int_0^T \mathbb{E}[(Lf)(g(t))] dt,$$

*i.e.*

$$(4.15) \quad \nu_T(f) = f(\mathbf{e}) + \frac{1}{2} \int_0^T \nu_t(Lf) dt.$$

*In other words,  $\nu_t$  weakly solves the heat equation*

$$\partial_t \nu_t = \frac{1}{2} L \nu_t \text{ with } \lim_{t \downarrow 0} \nu_t = \delta_{\mathbf{e}}.$$



*Proof.* Integrating Equation (4.11) shows

$$(4.16) \quad f(g(T)) = f(\mathbf{e}) + N_T + \frac{1}{2} \int_0^T Lf(g(\tau)) d\tau$$

where

$$N_t := \int_0^t f'(g(\tau)) dg(\tau) = \int_0^t f'(g(\tau)) \left( dB(\tau), dB_0(\tau) + \frac{1}{2} dM_\tau \right)$$

and  $M_t = \int_0^t \omega(B(\tau), dB(\tau))$ . Using Eqs. (4.12) and (4.13) there exists  $C = C(P, \|\omega_0\|) < \infty$  such that

$$\begin{aligned} d\langle N \rangle_t &:= |dN_t|^2 = \langle f'(g_t) \otimes f'(g_t), dg_t \otimes dg_t \rangle \\ &= \sum_{j=1}^{\infty} \left| f'(g(t)) \left( e_j, \frac{1}{2} \omega(B(t), e_j) \right) \right|^2 dt + \sum_{\ell=1}^d |f'(g(t))(0, f_\ell)|^2 dt \\ &= \sum_{j=1}^n \left| f'(g(t)) \left( e_j, \frac{1}{2} \omega(B(t), e_j) \right) \right|^2 dt + \sum_{\ell=1}^d |f'(g(t))(0, f_\ell)|^2 dt \\ &\leq C_1(P, \|\omega_0\|) (1 + \|PB(t)\|_H + \|B_0(t)\|_C)^p \left( \|B(t)\|_W^2 + 1 \right) dt \\ &\leq C (1 + \|B(t)\|_W + \|B_0(t)\|_C)^{p+2} dt, \end{aligned}$$

wherein we have used Equation (3.43) for the last inequality. From this inequality and either of Equations (2.3) or (2.4), we find

$$\mathbb{E}[\langle N \rangle_T] \leq C \int_0^T \mathbb{E} (1 + \|B(t)\|_W + \|B_0(t)\|_C)^{p+2} dt < \infty$$

and hence that  $N_t$  is a square integrable martingale. Therefore we may take the expectation of Equation (4.16) which implies Equation (4.14).  $\square$

### 4.3. Finite Dimensional Approximations.

**Proposition 4.6.** *Let  $\{P_n\}_{n=1}^\infty \subset \text{Proj}(W)$  be as in Eq. (4.3) and*

$$(4.17) \quad B_n(t) := P_n B(t) \in P_n H \subset H \subset W.$$

*Then*

$$(4.18) \quad \lim_{n \rightarrow \infty} \mathbb{E} \left[ \max_{0 \leq t \leq T} \|B(t) - B_n(t)\|_W^p \right] = 0 \text{ for all } p \in [1, \infty),$$

*and*

$$(4.19) \quad \lim_{n \rightarrow \infty} \max_{0 \leq t \leq T} \|B(t) - B_n(t)\|_W = 0 \text{ a.s.}$$

*Proof.* Let  $\{w_k\}_{k=1}^\infty \subset W$  be a countable dense set and for each  $k \in \mathbb{N}$ , choose  $\varphi_k \in W^*$  such that  $\|\varphi_k\|_{W^*} = 1$  and  $\varphi_k(w_k) = \|w_k\|_W$ . We then have,

$$\|w\|_W = \sup_k |\varphi_k(w)| = \sup_k \text{Re } \varphi_k(w) \text{ for all } w \in W.$$

By [8, Theorem 3.5.7] with  $A = I$ , if  $\varepsilon_n(t) := B(t) - B_n(t)$ , then

$$(4.20) \quad \lim_{n \rightarrow \infty} \mathbb{E} \|\varepsilon_n(T)\|_W^p = 0 \text{ for all } p \in [1, \infty).$$

Since  $\{\varphi_k(\varepsilon_n(t))\}_{t \geq 0}$  is (up to a multiplicative factor) a standard Brownian motion,  $\{|\varphi_k(\varepsilon_n(t))|\}_{t \geq 0}$  is a submartingale for each  $k \in \mathbb{N}$  and therefore so is

$\{\|\varepsilon_n(t)\| = \sup_k |\varphi_k(\varepsilon_n(t))|\}_{t \geq 0}$ . Hence, according to Doob's inequality, for each  $p \in [1, \infty)$  there exists  $C_p < \infty$  such that

$$(4.21) \quad \mathbb{E} \left[ \max_{t \leq T} \|\varepsilon_n(t)\|_W \right]^p \leq C_p \mathbb{E} \|\varepsilon_n(T)\|_W^p.$$

Combining Equation (4.21) with Equation (4.20) proves Equation (4.18). Equation (4.19) now follows from Equation (4.18) and [11, Proposition 2.11]. To apply this proposition, let  $E$  be the Banach space,  $C([0, T], W)$  equipped with the sup-norm, and let  $\xi_k := \ell_k(B(\cdot)) e_k \in E$  for all  $k \in \mathbb{N}$ .  $\square$

**Lemma 4.7** (Finite Dimensional Approximations to  $g(t)$ ). *For  $P \in \text{Proj}(W)$ ,  $Q := I_W - P$ , let  $g_P(t)$  be the Brownian motion on  $G_P$  defined by*

$$g_P(t) := \left( PB(t), B_0(t) + \frac{1}{2} \int_0^t \omega(PB(\tau), PdB(\tau)) \right).$$

Then

$$(4.22) \quad g(t) = g_P(t) \left( QB(t), \frac{1}{2} \int_0^t [2\omega(QB(\tau), PdB(\tau)) + \omega(QB(\tau), QdB(\tau))] \right),$$

and

$$(4.23) \quad g_P(t)^{-1} \pi_P(g(t)) = \frac{1}{2} \left( 0, \int_0^t [\omega(B(\tau), dB(\tau)) - \omega(PB(\tau), PdB(\tau))] \right).$$

Also, if  $\{P_n\}_{n=1}^\infty \subset \text{Proj}(W)$  are as in Eq. (4.3) and

$$(4.24) \quad g_n(t) = g_{P_n}(t) = \left( P_n B(t), B_0(t) + \frac{1}{2} \int_0^t \omega(P_n B(\tau), dP_n B(\tau)) \right),$$

then

$$(4.25) \quad \lim_{n \rightarrow \infty} \mathbb{E} \left[ \max_{0 \leq t \leq T} \|g(t) - g_n(t)\|_{\mathfrak{g}}^p \right] = 0$$

for all  $1 \leq p < \infty$ .

*Proof.* A simple computation shows

$$\begin{aligned} l_{g_P(t)^{-1}*} \circ dg_P(t) &= \begin{pmatrix} dPB(t), dB_0(t) + \frac{1}{2} \omega(PB(t), PdB(t)) \\ + \frac{1}{2} \omega(-PB(t), PdB(t)) \end{pmatrix} \\ &= (dPB(t), dB_0(t)) = d(PB(t), B_0(t)). \end{aligned}$$

Hence it follows that  $g_P$  solves the stochastic differential equation,

$$dg_P(t) = l_{g_P(t)*} \circ d(PB(t), B_0(t)) \quad \text{with } g_P(0) = 0$$

and therefore  $g_P$  is a  $G_P$ -valued Brownian motion. The proof of the equalities in Equations (4.22) and (4.23) follows by elementary manipulations which are left to the reader.

In light of Equation (4.18) of Proposition 4.6, to prove the last assertion we must show

$$(4.26) \quad \lim_{n \rightarrow \infty} \mathbb{E} \left[ \max_{0 \leq t \leq T} |M_t(n)|^p \right] = 0,$$

where  $M_t(n)$  is the local martingale defined by

$$M_t(n) := \int_0^t [\omega(B(\tau), dB(\tau)) - \omega(B_n(\tau), dB_n(\tau))].$$

Since

$$\begin{aligned} \langle M(n) \rangle_T &= \sum_{j=1}^{\infty} \int_0^T \|\omega(B(\tau), e_j)\|_{\mathbf{C}}^2 d\tau + \sum_{j=1}^n \int_0^T \|\omega(B_n(\tau), e_j)\|_{\mathbf{C}}^2 d\tau \\ &\quad - 2 \sum_{j=1}^n \int_0^T \langle \omega(B(\tau), e_j), \omega(B_n(\tau), e_j) \rangle_{\mathbf{C}} d\tau \end{aligned}$$

and

$$\frac{2}{T^2} \mathbb{E}[\langle M(n) \rangle_T] = \sum_{j,k=1}^{\infty} \|\omega(e_k, e_j)\|_{\mathbf{C}}^2 - \sum_{k=1}^n \sum_{j=1}^n \|\omega(e_k, e_j)\|_{\mathbf{C}}^2 \rightarrow 0$$

as  $n \rightarrow \infty$ , it follows by the Burkholder-Davis-Gundy inequalities that  $M(n)$  is a martingale and Equation (4.26) holds for  $p = 2$  and hence for  $p \in [1, 2]$ .

By Doob's maximal inequality ([34, Proposition 7.16]), to prove Equation (4.26) for  $p \geq 2$ , it suffices to show  $\lim_{n \rightarrow \infty} \mathbb{E}[|M_T(n)|^p] = 0$ . However,  $M_T(n)$  has Itô's chaos expansion terminating at degree two and hence by a theorem of Nelson (see [44, Lemma 2 on p. 415] and [43, pp. 216-217]) for each  $j \in \mathbb{N}$  there exists  $c_j < \infty$  such that  $\mathbb{E}[M_T^{2j}(n)] \leq c_j [\mathbb{E}M_T^2(n)]^j$ . (This result also follows from Nelson's hypercontractivity for the Ornstein-Uhlenbeck operator.) This clearly suffices to complete the proof of the theorem.  $\square$

**Lemma 4.8.** *For all  $P \in \text{Proj}(W)$  and  $t > 0$ , let  $\nu_t^P := \text{Law}(g_P(t))$ . Then  $\nu_t^P(dx) = p_t^P(e, x) dx$ , where  $dx$  is the Riemannian volume measure (equal to a Haar measure)  $p_t^P(x, y)$  is the heat kernel on  $G_P$ .*

*Proof.* An application of Corollary 4.5 with  $G$  replaced by  $G_P$  implies that  $\nu_t^P = \text{Law}(g_P(t))$  is a weak solution to the heat equation on  $G_P$ . The result now follows as an application of [17, Theorem 2.6].  $\square$

**Corollary 4.9.** *For any  $T > 0$ , the heat kernel measure,  $\nu_T$ , is invariant under the inversion map,  $g \mapsto g^{-1}$  for any  $g \in G$ .*

*Proof.* It is well known (see for example [20, Proposition 3.1]) that heat kernel measures based at the identity of a finite-dimensional Lie group are invariant under inversion. Now suppose that  $f : G \rightarrow \mathbb{R}$  is a bounded continuous function. By passing to a subsequence if necessary, we may assume that the sequence of  $G$ -valued random variables,  $\{g_n(T)\}_{t \geq 0}$ , in Lemma 4.7 converges almost surely to  $g(T)$ . Therefore by the dominated convergence theorem,

$$\mathbb{E}f(g(T)^{-1}) = \lim_{n \rightarrow \infty} \mathbb{E}f(g_n(T)^{-1}) = \lim_{n \rightarrow \infty} \mathbb{E}f(g_n(T)) = \mathbb{E}f(g(T)).$$

This completes the proof because  $\nu_T$  is the law of  $g(T)$ .  $\square$

We are now going to give exponential bounds which are much stronger than the moment estimates in Equation (4.9) of Proposition 4.1. Before doing so we need to recall the following result of Cameron-Martin and Kac, [9, 33].

**Lemma 4.10** (Cameron–Martin and Kac). *Let  $\{b_s\}_{s \geq 0}$  be a one dimensional Brownian motion. Then for any  $T > 0$  and  $\lambda \in [0, \frac{\pi}{2T})$ ;*

$$(4.27) \quad \mathbb{E} \left[ \exp \left( \frac{\lambda^2}{2} \int_0^T b_s^2 ds \right) \right] = [\cos(\lambda T)]^{-1/2} < \infty.$$

*Proof.* When  $T = 1$ , simply follow the proof of [31, Equation (6.9) on p. 472] with  $\lambda$  replaced by  $-\lambda^2$ . For general  $T > 0$ , by a change of variables and a Brownian motion scaling we have

$$\int_0^T b_s^2 ds = T \int_0^1 b_{tT}^2 dt \stackrel{d}{=} T^2 \int_0^1 b_t^2 dt.$$

Therefore,

$$(4.28) \quad \mathbb{E} \left[ \exp \left( \frac{\lambda^2}{2} \int_0^T b_s^2 ds \right) \right] = \mathbb{E} \left[ \exp \left( \frac{\lambda^2 T^2}{2} \int_0^1 b_s^2 ds \right) \right] \\ = \cos^{-1/2} \left( \sqrt{\lambda^2 T^2} \right)$$

provided that  $\lambda \in [0, \frac{\pi}{2T})$ . □

**Remark 4.11.** For our purposes below, all we really need later from Lemma 4.10 is the qualitative statement that for  $\lambda T > 0$  sufficiently small

$$(4.29) \quad \mathbb{E} \left[ \exp \left( \frac{\lambda^2}{2} \int_0^T b_s^2 ds \right) \right] = 1 + \frac{\lambda^2 T^2}{4} + O(\lambda^4 T^4).$$

Instead of using Lemma 4.10 we can derive this statement as an easy consequence of the scaling identity in Equation (4.28) along with the analyticity (use Fernique’s theorem) of the function,

$$F(z) := \mathbb{E} \left[ \exp \left( z \int_0^1 b_s^2 ds \right) \right] \text{ for } |z| \text{ small.}$$

**Proposition 4.12.** *If  $\{N_t\}_{t \geq 0}$  is a continuous local martingale such that  $N_0 = 0$ . Then*

$$(4.30) \quad \mathbb{E} e^{|N_t|} \leq 2 \sqrt{\mathbb{E} [e^{2\langle N \rangle_t}]}.$$

*Proof.* By Itô’s formula, we know that

$$Z_t := e^{2N_t - \langle 2N \rangle_t / 2} = e^{2N_t - 2\langle N \rangle_t}$$

is a non-negative local martingale. If  $\{\sigma_n\}_{n=1}^\infty$  is a localizing sequence of stopping times for  $Z$ , then, by Fatou’s lemma,

$$\mathbb{E} [Z_t | \mathcal{B}_s] \leq \liminf_{n \rightarrow \infty} \mathbb{E} [Z_t^{\sigma_n} | \mathcal{B}_s] = \liminf_{n \rightarrow \infty} Z_s^{\sigma_n} = Z_s.$$

This shows that  $Z$  is a supermartingale and in particular that  $\mathbb{E} [Z_t] \leq \mathbb{E} Z_0 = 1$ .

By the Cauchy-Schwarz inequality we find

$$(4.31) \quad \mathbb{E} [e^{N_t}] = \mathbb{E} [e^{N_t - \langle N \rangle_t} e^{\langle N \rangle_t}] \\ \leq \sqrt{\mathbb{E} [e^{2N_t - 2\langle N \rangle_t}] \cdot \mathbb{E} [e^{2\langle N \rangle_t}]} = \sqrt{\mathbb{E} [Z_t] \cdot \mathbb{E} [e^{2\langle N \rangle_t}]} \\ \leq \sqrt{\mathbb{E} [e^{2\langle N \rangle_t}]}$$

Applying this inequality with  $N$  replaced by  $-N$  and using  $e^{|x|} \leq e^x + e^{-x}$  easily give Equation (4.30).  $\square$

**Proposition 4.13.** *Let  $n \in \mathbb{N}$ ,  $T > 0$ ,  $d = \dim_{\mathbb{R}} \mathbf{C}$ ,*

$$(4.32) \quad \gamma := \sup \left\{ \sum_{j=1}^{\infty} |\langle \omega(h, e_j), c \rangle_{\mathbf{C}}|^2 : \|h\|_H = \|c\|_{\mathbf{C}} = 1 \right\} \leq \|\omega\|_2^2 < \infty$$

and for  $P \in \text{Proj}(W)$  let  $B_P(t) := PB(t)$ . Then for all

$$(4.33) \quad 0 \leq \lambda < \frac{\pi}{4dT\sqrt{\gamma}},$$

$$(4.34) \quad \sup_{P \in \text{Proj}(W)} \mathbb{E} \left[ \exp \left( \lambda \left\| \int_0^t \omega(B_P(\tau), dB_P(\tau)) \right\|_{\mathbf{C}} \right) \right] < \infty$$

and

$$(4.35) \quad \mathbb{E} \left[ \exp \left( \lambda \left\| \int_0^t \omega(B(\tau), dB(\tau)) \right\|_{\mathbf{C}} \right) \right] < \infty.$$

*Proof.* Equation (4.35) follows by choosing  $\{P_n\}_{n=1}^{\infty} \subset \text{Proj}(W)$  as in Eq. (4.3) and then using Fatou's lemma in conjunction with the estimate in Equation (4.34). So we need only to concentrate on proving Equation (4.34).

Fix a  $P \in \text{Proj}(W)$  as in Equation (3.42) and let

$$M_t^P := \int_0^t \omega(B_P(\tau), dB_P(\tau)).$$

If  $\{f_\ell\}_{\ell=1}^d$  is an orthonormal basis for  $\mathbf{C}$ , then

$$\|M_t^P\|_{\mathbf{C}} \leq \sum_{\ell=1}^d |\langle M_t^P, f_\ell \rangle_{\mathbf{C}}|,$$

and it follows by Hölder's inequality and the martingale estimate in Proposition 4.12 that

$$(4.36) \quad \begin{aligned} \mathbb{E} \left[ e^{\lambda \|M_t^P\|_{\mathbf{C}}} \right] &\leq \mathbb{E} \left[ e^{\lambda \sum_{\ell=1}^d |\langle M_t^P, f_\ell \rangle_{\mathbf{C}}|} \right] \leq \prod_{\ell=1}^d \left( \mathbb{E} \left[ e^{\lambda d |\langle M_t^P, f_\ell \rangle_{\mathbf{C}}|} \right] \right)^{1/d} \\ &\leq \prod_{\ell=1}^d \left( 2 \sqrt{\mathbb{E} \left[ e^{2\lambda^2 d^2 \langle \langle M_t^P, f_\ell \rangle_{\mathbf{C}} \rangle_t} \right]} \right)^{1/d} \\ &= 2 \prod_{\ell=1}^d \left( \mathbb{E} \left[ e^{2\lambda^2 d^2 \langle \langle M_t^P, f_\ell \rangle_{\mathbf{C}} \rangle_t} \right] \right)^{1/2d}. \end{aligned}$$

We will now evaluate each term in the product in Eq. (4.36). So let  $c := f_\ell$  and  $N_t := \langle M_t^P, c \rangle_{\mathbf{C}}$ , and  $Q_P : H \rightarrow H$  and  $Q : H \rightarrow H$  be the unique non-negative symmetric operators such that, for all  $h \in H$ ,

$$\sum_{j=1}^n |\langle \omega(P h, e_j), c \rangle_{\mathbf{C}}|^2 = \langle Q_P h, h \rangle_H \quad \text{for all } h \in H$$

and

$$\sum_{j=1}^{\infty} |\langle \omega(h, e_j), c \rangle_{\mathbf{C}}|^2 = \langle Qh, h \rangle_H \quad \text{for all } h \in H.$$

Also let  $\{q_l(P)\}_{l=1}^{\infty}$  be the eigenvalues listed in decreasing order (counted with multiplicities) for  $Q_P$  and observe that

$$(4.37) \quad q_1(P) = \sup_{h \neq 0} \frac{\langle Q_P h, h \rangle}{\|h\|_H^2} \leq \sup_{h \neq 0} \frac{\langle Q_P h, Ph \rangle}{\|h\|_H^2} \leq \sup_{h \neq 0} \frac{\langle Qh, h \rangle}{\|h\|_H^2} \leq \gamma.$$

With this notation, the quadratic variation of  $N$  is given by

$$(4.38) \quad \langle N \rangle_T = \int_0^T \sum_{j=1}^n |\langle \omega(B_P(t), e_j), c \rangle_{\mathbf{C}}|^2 dt = \int_0^T \langle Q_P B_P(t), B_P(t) \rangle_H dt.$$

Moreover, by expanding  $B_P(\tau)$  in an orthonormal basis of eigenvectors of  $Q_P|_{PH}$  it follows that

$$(4.39) \quad \langle N \rangle_T = \sum_{l=1}^n q_l(P) \int_0^T b_l^2(\tau) d\tau$$

where  $\{b_l\}_{l=1}^n$  is a sequence of independent Brownian motions. Hence it follows that

$$(4.40) \quad \begin{aligned} \mathbb{E} \left[ e^{2\lambda^2 d^2 \langle \langle M^P, f_\ell \rangle_{\mathbf{C}} \rangle_T} \right] &= \mathbb{E} \left[ e^{2\lambda^2 d^2 \langle N \rangle_T} \right] \\ &= \prod_{l=1}^n \mathbb{E} \left[ \exp \left( 2\lambda^2 d^2 q_l(P) \int_0^T b_l^2(\tau) d\tau \right) \right]. \end{aligned}$$

If Eq. (4.33) holds then (using Eq. (4.37))

$$2\lambda d \sqrt{q_1(P)} = \sqrt{4\lambda^2 d^2 q_1(P)} \leq 2\lambda d \sqrt{\gamma} < \pi/2T$$

and we may apply Lemma 4.10 to find

$$(4.41) \quad \begin{aligned} \mathbb{E} \left[ \exp \left( 2\lambda^2 d^2 q_l(P) \int_0^T b_l^2(\tau) d\tau \right) \right] &= \frac{1}{\sqrt{\cos \left( 2\lambda d \sqrt{q_l(P)} T \right)}} \\ &= \exp \left( -\frac{1}{2} \ln \cos \left( 2\lambda d \sqrt{q_l(P)} T \right) \right). \end{aligned}$$

Moreover, a simple calculus exercise shows for any  $k \in (0, \pi/2)$  there exists  $c(k) < \infty$  such that  $-\frac{1}{2} \ln \cos(x) \leq c(k) x^2$  for  $0 \leq x \leq k$ . Taking  $k = 2\lambda d \sqrt{\gamma} T$  we may apply this estimate to Eq. (4.41) and combine the result with Eq. (4.40) to find

$$\mathbb{E} \left[ e^{2\lambda^2 d^2 \langle \langle M^P, f_\ell \rangle_{\mathbf{C}} \rangle_T} \right] \leq \prod_{l=1}^n \exp \left( c(k) 4\lambda^2 d^2 T^2 q_l(P) \right) = \exp \left( c(k) 4\lambda^2 d^2 T^2 \text{tr}(Q_P) \right).$$

Since  $Q_P \leq P Q P$ , we have

$$\text{tr } Q_P \leq \text{tr } Q = \sum_{l=1}^{\infty} \langle Q e_l, e_l \rangle_H = \sum_{j,l=1}^{\infty} |\langle \omega(e_l, e_j), c \rangle_{\mathbf{C}}|^2 = \|\langle \omega(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_2^2 < \infty.$$

Combining the last two equations (recalling that  $c = f_\ell$ ) then shows,

$$(4.42) \quad \mathbb{E} \left[ e^{2\lambda^2 d^2 \langle \langle M^P, f_\ell \rangle_{\mathbf{C}} \rangle_T} \right] \leq \exp \left( c(k) 4\lambda^2 d^2 T^2 \|\langle \omega(\cdot, \cdot), f_\ell \rangle_{\mathbf{C}}\|_2^2 \right).$$

Using this estimate back in Eq. (4.36) gives,

$$(4.43) \quad \begin{aligned} \mathbb{E} \left[ e^{\lambda \|M_t^P\|_{\mathbf{C}}} \right] &\leq 2 \exp \left( c(k) 2\lambda^2 dT^2 \sum_{\ell=1}^d \|\langle \omega(\cdot, \cdot), f_{\ell} \rangle_{\mathbf{C}}\|_2^2 \right) \\ &= 2 \exp \left( c(k) 2\lambda^2 dT^2 \|\omega\|_2^2 \right) \end{aligned}$$

which completes the proof as this last estimate is independent of  $P \in \text{Proj}(W)$ .  $\square$

**Proposition 4.14.** *Suppose that  $\nu$  and  $\mu$  are Gaussian measures on  $W$  such  $q_{\nu}(f) := \nu(f^2) \leq q_{\mu}(f) := \mu(f^2)$  for all  $f \in W_{\mathbb{R}}^*$ . If  $g : [0, \infty) \rightarrow [0, \infty)$  is a non-negative, non-decreasing,  $C^1$ -function, then*

$$\int_W g(\|w\|) d\nu(w) \leq \int_W g(\|w\|) d\mu(w).$$

*Proof.* Theorem 3.3.6 in [8, p. 107] states that if  $q_{\nu} \leq q_{\mu}$  then  $\mu(A) \leq \nu(A)$  for every Borel set  $A$  which is convex and balanced. In particular, since  $B_t := \{w \in W : \|w\| < t\}$  is convex and balanced, it follows that  $\mu(B_t) \leq \nu(B_t)$  or equivalently that  $1 - \nu(B_t) \leq 1 - \mu(B_t)$  for all  $t \geq 0$ . Since

$$(4.44) \quad \begin{aligned} \int_W g(\|w\|) d\nu(w) &= \int_W \left[ g(0) + \int_0^{\infty} 1_{t \leq \|w\|} g'(t) dt \right] d\nu(w) \\ &= g(0) + \int_0^{\infty} \left( g'(t) \int_W 1_{t \leq \|w\|} d\nu(w) \right) dt \\ &= g(0) + \int_0^{\infty} g'(t) [1 - \nu(B_t)] dt \end{aligned}$$

with the same formula holding when  $\nu$  is replaced by  $\mu$ , it follows that

$$\begin{aligned} \int_W g(\|w\|) d\nu(w) &= g(0) + \int_0^{\infty} g'(t) [1 - \nu(B_t)] dt \\ &\leq g(0) + \int_0^{\infty} dt g'(t) [1 - \mu(B_t)] = \int_W g(\|w\|) d\mu(w). \end{aligned}$$

$\square$

**Definition 4.15.** Let  $\rho^2 : G \rightarrow [0, \infty)$  be defined as

$$\rho^2(w, c) := \|w\|_W^2 + \|c\|_{\mathbf{C}}.$$

In analogy to Gross' theory of measurable semi-norms (see e.g. Definition 5 in [27]) in the abstract Wiener space setting and in light of Theorem 3.12, we view  $\rho$  as a “measurable” extension of  $d_{G_{CM}}$ .

**Theorem 4.16** (Integrated Gaussian heat kernel bounds). *There exists a  $\delta > 0$  such that for all  $\varepsilon \in (0, \delta)$ ,  $T > 0$ ,  $p \in [1, \infty)$ ,*

$$(4.45) \quad \sup_{P \in \text{Proj}(W)} \mathbb{E} \left[ e^{\frac{\varepsilon}{T} \rho^2(g_P(T))} \right] < \infty \text{ and } \int_G e^{\frac{\varepsilon}{T} \rho^2(g)} d\nu_T(g) < \infty$$

whenever  $\varepsilon < \delta$ .

*Proof.* Let  $\varepsilon' := \varepsilon/T$ . For  $P \in \text{Proj}(W)$ ,

$$\rho^2(g_P(T)) \leq \|B_P(T)\|_W^2 + \|B_0(T)\|_{\mathbf{C}} + \frac{1}{2} \|N_P(T)\|_{\mathbf{C}},$$

where  $N_P(T) := \int_0^T \omega(B_P(t), dB_P(t))$  and therefore,

$$\mathbb{E} \left[ e^{\varepsilon' \rho^2(g_P(T))} \right] \leq \mathbb{E} \left[ e^{\varepsilon' [\|B_P(T)\|_W^2 + \frac{1}{2} \|N_P(T)\|_{\mathbf{C}}]} \right] \cdot \mathbb{E} \left[ e^{\varepsilon' \|B_0(T)\|_{\mathbf{C}}} \right].$$

Moreover, by Hölder's inequality we have,

$$\begin{aligned} \mathbb{E} \left[ e^{\varepsilon' \rho^2(g_P(T))} \right] &\leq \mathbb{E} \left[ e^{\varepsilon' \|B_0(T)\|_{\mathbf{C}}} \right] \sqrt{\mathbb{E} \left[ e^{2\varepsilon' \|B_P(T)\|_W^2} \right] \cdot \mathbb{E} \left[ e^{\varepsilon' \|N_P(T)\|_{\mathbf{C}}} \right]} \\ &\leq \mathbb{E} \left[ e^{\varepsilon' \|B_0(T)\|_{\mathbf{C}}} \right] \sqrt{\mathbb{E} \left[ e^{2\varepsilon' \|B(T)\|_W^2} \right] \cdot \sup_{P' \in \text{Proj}(W)} \mathbb{E} \left[ e^{\varepsilon' \|N_{P'}(T)\|_{\mathbf{C}}} \right]} \end{aligned}$$

wherein we have made use of Proposition 4.14 to conclude that

$$\mathbb{E} \left[ e^{2\varepsilon' \|B_P(T)\|_W^2} \right] \leq \mathbb{E} \left[ e^{2\varepsilon' \|B(T)\|_W^2} \right] = \mathbb{E} \left[ e^{2\varepsilon' T \|B(1)\|_W^2} \right]$$

which is finite by Fernique's theorem provided  $2\varepsilon = 2\varepsilon' T < \delta'$  for some  $\delta' > 0$ . Similarly by Proposition 4.13,

$$\sup_{P' \in \text{Proj}(W)} \mathbb{E} \left[ e^{\varepsilon' \|N_{P'}(T)\|_{\mathbf{C}}} \right] < \infty$$

provided  $\varepsilon = \varepsilon' T < \frac{\pi}{4\sqrt{\gamma}}$ . The assertion in Equation (4.45) now follows from these observations and the fact that  $\mathbb{E} \left[ e^{\varepsilon' \|B_0(T)\|_{\mathbf{C}}} \right] < \infty$  for all  $\varepsilon' > 0$ .  $\square$

## 5. PATH SPACE QUASI-INVARIANCE

**Notation 5.1.** Let  $W_T(G)$  denote the collection of continuous paths,  $g : [0, T] \rightarrow G$  such that  $g(0) = \mathbf{e}$ . Moreover, if  $V$  is a separable Hilbert space, let  $\mathcal{H}_T(V)$  denote the collection of absolutely continuous functions (see [14, pages 106-107]),  $h : [0, T] \rightarrow V$  such that  $h(0) = 0$  and

$$\|h\|_{\mathcal{H}_T(V)} := \left( \int_0^T \|\dot{h}(t)\|_V^2 dt \right)^{1/2} < \infty.$$

By polarization, we endow  $\mathcal{H}_T(V)$  with the inner product

$$\langle h, k \rangle_{\mathcal{H}_T(V)} = \int_0^T \langle \dot{h}(t), \dot{k}(t) \rangle_V dt.$$

**Theorem 5.2** (Path space quasi-invariance). *Suppose  $T > 0$ ,  $k(\cdot) = (A(\cdot), a(\cdot)) \in \mathcal{H}_T(\mathfrak{g}_{CM})$  (thought of as a finite energy path in  $G_{CM}$ ), and  $g(\cdot)$  is the  $G$ -valued Brownian motion in Equation (4.10). Then over the finite time interval,  $[0, T]$ , the laws of  $k \cdot g$  and  $g$  are equivalent, i.e. they are mutually absolutely continuous relative to one another. More precisely, if  $F : W_T(G) \rightarrow [0, \infty]$  is a measurable function, then*

$$(5.1) \quad \mathbb{E} [F(k \cdot g)] = \mathbb{E} \left[ \tilde{Z}_k(B, B_0) F(g) \right],$$

where

$$(5.2) \quad \tilde{Z}_k(B, B_0) := \exp \left( \begin{aligned} &\int_0^T \left\langle \dot{A}(t), dB(t) \right\rangle_H - \frac{1}{2} \int_0^T \left\| \dot{A}(t) \right\|_H^2 dt \\ &+ \int_0^T \left\langle \dot{a}(t) + \frac{1}{2} \omega \left( A(t) - 2B(t), \dot{A}(t) \right), dB_0(t) \right\rangle_{\mathbf{C}} \\ &- \frac{1}{2} \int_0^T \left\| \dot{a}(t) + \frac{1}{2} \omega \left( A(t) - 2B(t), \dot{A}(t) \right) \right\|_{\mathbf{C}}^2 dt \end{aligned} \right).$$



Moreover, Equation (5.2) is valid for all measurable functions,  $F : W_T(G) \rightarrow \mathbb{C}$  such that

$$\mathbb{E}[|F(k \cdot g)|] = \mathbb{E}\left[\tilde{Z}_k(B, B_0) |F(g)|\right] < \infty.$$

*Proof.* The Cameron–Martin theorem states (see for example, [36, Theorem 1.2 on p. 113]) that

$$(5.3) \quad \mathbb{E}[F(B, B_0)] = \mathbb{E}[Z_k(B, B_0) F((B, B_0) - k)],$$

where

$$(5.4) \quad Z_k(B, B_0) := \exp\left(\begin{array}{l} \int_0^T \left[\langle \dot{A}(t), dB(t) \rangle_H + \langle \dot{a}(t), dB_0(t) \rangle_{\mathbb{C}} \right] \\ - \frac{1}{2} \int_0^T \left[ \|\dot{A}(t)\|_H^2 + \|\dot{a}(t)\|_{\mathbb{C}}^2 \right] dt \end{array}\right).$$

Since

$$(5.5) \quad \begin{aligned} (k \cdot g)(t) = \\ \left( B(t) + A(t), B_0(t) + a(t) + \frac{1}{2} \int_0^t \omega(B(\tau), dB(\tau)) + \frac{1}{2} \omega(A(t), B(t)) \right) \end{aligned}$$

is mapped to

$$\left( B(t), B_0(t) + \frac{1}{2} \int_0^t \omega((B-A)(\tau), d(B-A)(\tau)) + \frac{1}{2} \omega(A(t), (B-A)(t)) \right)$$

under the transformation  $B \rightarrow B - A$  and  $B_0 \rightarrow B_0 - a$ , we may conclude from Equation (5.3) that

$$(5.6) \quad \mathbb{E}[F(k \cdot g)] = \mathbb{E}[Z_k(B, B_0) F(B, B_0 + c)],$$

where

$$c(t) = \frac{1}{2} \int_0^t \omega((B-A)(\tau), d(B-A)(\tau)) + \frac{1}{2} \omega(A(t), (B-A)(t)).$$

By taking the differential of  $c$ , one easily shows that

$$c(t) = \frac{1}{2} \int_0^t \omega(B(\tau), dB(\tau)) + u_B(t),$$

where

$$(5.7) \quad u_B(t) := \frac{1}{2} \int_0^t \omega(A(\tau) - 2B(\tau), \dot{A}(\tau)) d\tau.$$

Hence Equation (5.6) may be rewritten as

$$(5.8) \quad \mathbb{E}[F(k \cdot g)] = \mathbb{E}\left[Z_k(B, B_0) F\left(B, B_0 + u_B + \frac{1}{2} \int_0^t \omega(B(t), dB(t))\right)\right].$$

Freezing the integration over  $B$  (i.e. using Fubini's theorem) we may use the Cameron–Martin theorem one more time to make the transformation,  $B_0 \rightarrow B_0 - u_B$ . Doing so gives

$$(5.9) \quad \begin{aligned} \mathbb{E}[F(k \cdot g)] &= \mathbb{E}\left[\tilde{Z}_k(B, B_0) F\left(\left(B, B_0 + \frac{1}{2} \int_0^t \omega(B(t), dB(t))\right)\right)\right] \\ &= \mathbb{E}\left[\tilde{Z}_k(B, B_0) F(g)\right], \end{aligned}$$

where  
(5.10)

$$\tilde{Z}_k(B, B_0) := Z_k(B, B_0 - u_B) \exp \left( \int_0^T \langle \dot{u}_B(t), dB_0(t) \rangle_{\mathbf{C}} - \frac{1}{2} \int_0^T \|\dot{u}_B(t)\|_{\mathbf{C}}^2 dt \right).$$

A little algebra shows that  $\tilde{Z}_k(B, B_0)$  defined in Equation (5.10) may be expressed as in Equation (5.2).  $\square$

**Remark 5.3.** The above proof fails if we try to use it to prove the right quasi-invariance on the path space measure, i.e. that  $g \cdot k$  has a law which is absolutely continuous to that of  $g$ . In this case

$$(g \cdot k)(t) = \left( B(t) + A(t), B_0(t) + a(t) + \frac{1}{2} \int_0^t \omega(B(\tau), dB(\tau)) - \frac{1}{2} \omega(A(t), B(t)) \right)$$

and then making the transformation,  $B \rightarrow B - A$  and  $B_0 \rightarrow B_0 - a$  gives

$$\mathbb{E}[F(g \cdot k)] = \mathbb{E}[Z_k(B, B_0) F(B, B_0 + c)]$$

where

$$c(t) = \frac{1}{2} \int_0^t \omega(B(\tau), dB(\tau)) + u_B(t)$$

and

$$u_B(t) = \frac{1}{2} \int_0^t [\omega(A, dA) - 2\omega(A, dB)].$$

The argument breaks down at this point since  $u_B$  is no longer absolutely continuous in  $t$ . Hence we can no longer use the Cameron – Martin theorem to translate away the  $u_B$  term.

**Proposition 5.4.** *There exists a  $\delta > 0$  and a function  $C(p, u) \in (0, \infty]$ , for  $1 < p < \infty$  and  $0 \leq u < \infty$ , which is non-decreasing in each of its variables,  $C(p, u) < \infty$  whenever*

$$(5.11) \quad p \leq \frac{1}{2} \left( 1 + \sqrt{1 + \delta/u} \right),$$

and,

$$(5.12) \quad \mathbb{E} \left[ \tilde{Z}_k(B, B_0)^p \right] \leq C \left( p, \|k\|_{\mathcal{H}_T(\mathfrak{g}_{CM})} \right) \text{ for all } k \in \mathcal{H}_T(\mathfrak{g}_{CM}).$$

*Proof.* For the purposes of this proof, let  $\mathbb{E}_{B_0}$  and  $\mathbb{E}_B$  denote the expectation relative to  $B_0$  and  $B$  respectively, so that by Fubini's theorem  $\mathbb{E} = \mathbb{E}_{B_0} \mathbb{E}_B = \mathbb{E}_B \mathbb{E}_{B_0}$ . We may write  $\tilde{Z}_k(B, B_0)$  as

$$\tilde{Z}_k(B, B_0) := \zeta(B) \exp \left( \int_0^T \langle \dot{a}(t) + \dot{u}_B(t), dB_0(t) \rangle_{\mathbf{C}} \right)$$

where

$$\zeta(B) := \exp \left( \int_0^T \langle \dot{A}(t), dB(t) \rangle_H - \frac{1}{2} \int_0^T \|\dot{A}(t)\|_H^2 dt - \frac{1}{2} \int_0^T \|\dot{a}(t) + \dot{u}_B(t)\|_{\mathbf{C}}^2 dt \right)$$

and  $u_B(t)$  is as in Equation (5.7). Hence it follows that,

$$\mathbb{E}_{B_0} \left[ \tilde{Z}_k(B, B_0)^p \right] = \zeta^p(B) \mathbb{E}_{B_0} \left[ \exp \left( p \int_0^T \langle \dot{a}(t) + \dot{u}_B(t), dB_0(t) \rangle_{\mathbf{C}} \right) \right]$$

$$(5.13) \quad = \zeta^p(B) \exp\left(\frac{p^2}{2} \int_0^T \|\dot{a}(t) + \dot{u}_B(t)\|_{\mathbf{C}}^2 dt\right) = UV$$

where

$$U := \exp\left(p \left(\int_0^T \langle \dot{A}(t), dB(t) \rangle_H - \frac{1}{2} \int_0^T \|\dot{A}(t)\|_H^2 dt\right)\right)$$

and

$$V = \exp\left(\frac{p^2 - p}{2} \int_0^T \|\dot{a}(t) + \dot{u}_B(t)\|_{\mathbf{C}}^2 dt\right).$$

Note that when  $p = 1$ , Equation (5.13) becomes

$$\mathbb{E}_{B_0} [\tilde{Z}_k(B, B_0)] = \exp\left(\int_0^T \langle \dot{A}(t), dB(t) \rangle_H - \frac{1}{2} \int_0^T \|\dot{A}(t)\|_H^2 dt\right),$$

from which it easily follows that

$$\mathbb{E} [\tilde{Z}_k(B, B_0)] = \mathbb{E}_B \mathbb{E}_{B_0} [\tilde{Z}_k(B, B_0)] = 1.$$

Now suppose that  $p > 1$ . By the Cauchy – Schwarz inequality,

$$\mathbb{E} [\tilde{Z}_k(B, B_0)^p] = \mathbb{E}_B [UV] \leq (\mathbb{E}_B [V^2])^{1/2} (\mathbb{E}_B [U^2])^{1/2}.$$

Because

$$\begin{aligned} \mathbb{E} U^2 &= \exp\left(-p \int_0^T \|\dot{A}(t)\|_H^2 dt\right) \mathbb{E} \left[\exp\left(2p \int_0^T \langle \dot{A}(t), dB(t) \rangle_H\right)\right] \\ &= \exp\left(p \|A\|_{\mathcal{H}_T(H)}^2\right) \leq \exp\left(p \|k\|_{\mathcal{H}_T(\mathfrak{g}_{CM})}^2\right) < \infty, \end{aligned}$$

we have reduced the problem to estimating  $\mathbb{E} V^2$ . By elementary estimates we have

$$\begin{aligned} \|\dot{u}_B(t)\|_{\mathbf{C}}^2 &= \frac{1}{4} \left\| \omega\left(A(t) - 2B(t), \dot{A}(t)\right) \right\|_{\mathbf{C}}^2 \\ &\leq \frac{1}{4} \|\omega\|_0^2 \|A(t) - 2B(t)\|_W^2 \|\dot{A}(t)\|_W^2 \\ &\leq \frac{1}{2} \|\omega\|_0^2 \|\dot{A}(t)\|_W^2 \left(\|A(t)\|_W^2 + 4\|B(t)\|_W^2\right) \end{aligned}$$

and hence

$$(5.14) \quad \begin{aligned} \|\dot{a}(t) + \dot{u}_B(t)\|_{\mathbf{C}}^2 &\leq 2\|\dot{a}(t)\|_{\mathbf{C}}^2 + 2\|\dot{u}_B(t)\|_{\mathbf{C}}^2 \\ &= 2\|\dot{a}(t)\|_{\mathbf{C}}^2 + \|\omega\|_0^2 \|\dot{A}(t)\|_W^2 \left(\|A(t)\|_W^2 + 4 \sup_{0 \leq t \leq T} \|B(t)\|_W^2\right). \end{aligned}$$

By Equation (2.10) there exists  $c < \infty$  such that  $\|\cdot\|_W \leq c\|\cdot\|_H$ . Since

$$\|A(t)\|_H \leq \int_0^T \|\dot{A}(\tau)\|_H d\tau \leq \sqrt{T} \|A\|_{\mathcal{H}_T(H)},$$

we find

$$V^2 \leq C \exp\left(4(p^2 - p) c^2 \|\omega\|_0^2 \|A\|_{\mathcal{H}_T(H)}^2 \sup_{0 \leq t \leq T} \|B(t)\|_W^2\right)$$

where

$$C = \exp\left((p^2 - p) \left(2\|a\|_{\mathcal{H}_T(\mathbf{C})}^2 + c^4 T \|\omega\|_0^2 \|A\|_{\mathcal{H}_T(H)}^4\right)\right)$$

$$\leq C' \left( p, \|k\|_{\mathcal{H}_T(\mathfrak{g}_{CM})} \right) < \infty.$$

Now by Fernique's theorem as in Equation 2.4 there exists  $\delta' > 0$  such that

$$M := \mathbb{E} \left[ \exp \left( \delta' \sup_{0 \leq t \leq T} \|B(t)\|_W^2 \right) \right] < \infty$$

and hence it follows that

$$\mathbb{E}V^2 \leq C' \left( p, \|k\|_{\mathcal{H}_T(\mathfrak{g}_{CM})} \right) \cdot M < \infty$$

provided

$$4(p^2 - p) c^2 \|\omega\|_0^2 \|A\|_{\mathcal{H}_T(H)}^2 \leq 4(p^2 - p) c^2 \|\omega\|_0^2 \|k\|_{\mathcal{H}_T(\mathfrak{g}_{CM})}^2 \leq \delta'.$$

The latter condition holds provided

$$p \leq \frac{1 + \sqrt{1 + \delta / \|k\|_{\mathcal{H}_T(\mathfrak{g}_{CM})}^2}}{2}$$

where  $\delta := \left( c^2 \|\omega\|_0^2 \right)^{-1} \delta' > 0$ .  $\square$

**Definition 5.5.** We will say that a function,  $F : W_T(G) \rightarrow \mathbb{R}$  ( $W_T(G)$  as in Notation 5.1) is **polynomially bounded** if there exist constants  $K, M < \infty$  such that

$$(5.15) \quad |F(g)| \leq K \left( 1 + \sup_{t \in [0, T]} \|g(t)\|_G \right)^M \quad \text{for all } g \in W_T(G).$$

Given a finite energy path,  $k(t) = (A(t), a(t)) \in \mathfrak{g}_{CM}$ , we say that  $F$  is right  $k$  differentiable if

$$\frac{d}{ds} \Big|_0 F((sk) \cdot g) =: \left( \hat{k}F \right) (g)$$

exists for all  $g \in W_T(G)$ .

**Corollary 5.6** (Path space integration by parts). *Let  $k(\cdot) = (A(\cdot), a(\cdot)) \in \mathcal{H}_T(\mathfrak{g}_{CM})$  and  $F : W_T(G) \rightarrow \mathbb{R}$  be a  $k$ -differentiable function such that  $F$  and  $\hat{k}F$  are polynomial bounded functions on  $W_T(G)$ . Then*

$$(5.16) \quad \mathbb{E} \left[ \left( \hat{k}F \right) (g) \right] = \mathbb{E} [F(g) z_k]$$

where

$$(5.17) \quad z_k := \int_0^T \left[ \left\langle \dot{A}(t), dB(t) \right\rangle_H + \left\langle \dot{a}(t) - \omega(B(t), \dot{A}(t)), dB_0(t) \right\rangle_{\mathbf{C}} \right].$$

Moreover,  $\mathbb{E} |z_k|^p < \infty$  for all  $p \in [1, \infty)$ .

*Proof.* From Theorem 5.2, we have that for any  $s \in \mathbb{R}$

$$(5.18) \quad \mathbb{E} [F((sk) \cdot g)] = \mathbb{E} \left[ \tilde{Z}_{sk}(B, B_0) F(g) \right].$$

Formally differentiating this identity at  $s = 0$  and interchanging the derivatives with the expectations immediately leads to Equation (5.16). To make this rigorous we need only to verify that derivative interchanges are permissible. From Equations (3.8) and (5.15), there exists  $C(k) < \infty$  such that

$$\sup_{|s| \leq 1} \left| \frac{d}{ds} F((sk) \cdot g) \right| = \sup_{|s| \leq 1} \left| \left( \hat{k}F \right) ((sk) \cdot g) \right|$$

$$\begin{aligned} &\leq K \sup_{|s| \leq 1} \left( 1 + \sup_{t \in [0, T]} \|[sk(t)] \cdot g(t)\|_G \right)^M \\ &\leq C(k) \left( 1 + \sup_{t \in [0, T]} \|g(t)\|_G \right)^M \end{aligned}$$

wherein the last expression is integrable by Fernique's theorem and the moment estimate in Proposition 4.1. Therefore,

$$\frac{d}{ds} |_0 \mathbb{E} [F((sk) \cdot g)] = \mathbb{E} \left[ \frac{d}{ds} |_0 F((sk) \cdot g) \right] = \mathbb{E} \left[ (\hat{k}F)(g) \right].$$

To see that we may also differentiate the right side of Equation (5.18), observe that

$$\tilde{Z}_{sk}(B, B_0) = \exp(szk + s^2\beta + s^3\gamma + s^4\kappa)$$

where

$$\begin{aligned} \beta &= -\frac{1}{2} \int_0^T \|\dot{A}(t)\|_H^2 dt + \frac{1}{2} \int_0^T \left\langle \omega(A(t), \dot{A}(t)), dB_0(t) \right\rangle_{\mathbf{C}} \\ &\quad - \frac{1}{2} \int_0^T \|\dot{a}(t) - \omega(B(t), \dot{A}(t))\|_{\mathbf{C}}^2 dt, \\ \gamma &= -\frac{1}{2} \int_0^T \operatorname{Re} \left\langle \dot{a}(t) - \omega(B(t), \dot{A}(t)), \omega(A(t), \dot{A}(t)) \right\rangle_{\mathbf{C}} dt, \end{aligned}$$

and

$$\kappa = -\frac{1}{8} \int_0^T \|\omega(A(t), \dot{A}(t))\|_{\mathbf{C}}^2 dt.$$

Using Fernique's theorem again and estimates similar to those used in the proof of Proposition 5.4, one shows for any  $p \in [1, \infty)$  that there exists  $s_0(p) > 0$  such that

$$\mathbb{E} \left[ \sup_{|s| \leq s_0(p)} \left| \frac{d}{ds} \tilde{Z}_{sk}(B, B_0) \right|^p \right] < \infty.$$

Therefore we may differentiate past the expectation to find

$$\frac{d}{ds} |_0 \mathbb{E} [F(g) \tilde{Z}_{sk}(B, B_0)] = \mathbb{E} \left[ F(g) \frac{d}{ds} |_0 \tilde{Z}_{sk}(B, B_0) \right] = \mathbb{E} [F(g) z_k].$$

The fact that  $z_k$  has finite moments of all orders follows by the martingale arguments along with Nelson's theorem as described in the proof of Lemma 4.7. Alternatively, observe that  $\int_0^T \langle \dot{A}(t), dB(t) \rangle_H$  is Gaussian and hence has finite moments of all orders. If we let  $M_t := \int_0^t \langle \dot{a} - \omega(B, \dot{A}), dB_0 \rangle_{\mathbf{C}}$ , then  $M$  is a martingale such that

$$\langle M \rangle_T = \int_0^T \|\dot{a}(t) - \omega(B(t), \dot{A}(t))\|_{\mathbf{C}}^2 dt \leq C \left( 1 + \max_{0 \leq t \leq T} \|B(t)\|_W^2 \right).$$

So by Fernique's theorem,  $\mathbb{E}[\langle M \rangle_T^p] < \infty$  for all  $p < \infty$  and hence by the Burkholder-Davis-Gundy inequalities,  $\mathbb{E}|M_T|^p < \infty$  for all  $1 \leq p < \infty$ .  $\square$

## 6. HEAT KERNEL QUASI-INVARIANCE

In this section we will use the results of Section 5 to prove both quasi-invariance of the heat kernel measures,  $\{\nu_T\}_{T>0}$ , relative to left and right translations by elements of  $G_{CM}$ .

**Theorem 6.1** (Left quasi-invariance of the heat kernel measure). *Let  $T > 0$  and  $(A, a) \in G_{CM}$ . Then  $(A, a) \cdot g(T)$  and  $g(T)$  have equivalent laws. More precisely, if  $f : G \rightarrow [0, \infty]$  is a measurable function, then*

$$(6.1) \quad \mathbb{E}[f((A, a) \cdot g(T))] = \mathbb{E}[f(g(T)) \bar{Z}_k(g(T))],$$

where

$$(6.2) \quad \bar{Z}_k(g(T)) = \mathbb{E}[\zeta_{(A,a)}(B, B_0) | \sigma(g(T))]$$

and

$$(6.3) \quad \begin{aligned} \ln \zeta_{(A,a)}(B, B_0) := & \frac{1}{T} \langle A, B(T) \rangle_H - \frac{\|A\|_H^2}{2T^2} + \frac{1}{T} \int_0^T \langle a - \omega(B(t), A), dB_0(t) \rangle_{\mathbb{C}} \\ & - \frac{1}{2T^2} \int_0^T \|a - \omega(B(t), A)\|_{\mathbb{C}}^2 dt. \end{aligned}$$

*Proof.* An application of Theorem 5.2 with  $F(g) := f(g(T))$  and  $k(t) := \frac{t}{T}(A, a)$  implies

$$(6.4) \quad \begin{aligned} \mathbb{E}[f((A, a) \cdot g(T))] &= \mathbb{E}[F(\mathbf{k} \cdot g)] = \mathbb{E}[\tilde{Z}_k(B, B_0) \cdot F(g)] \\ &= \mathbb{E}[\tilde{Z}_k(B, B_0) f(g(T))], \end{aligned}$$

where after a little manipulation one shows,  $\tilde{Z}_k(B, B_0) = \zeta_{(A,a)}(B, B_0)$ . By conditioning on  $\sigma(g(T))$  we can also write Equation (6.4) as in Equation (6.1).  $\square$

**Corollary 6.2** (Right quasi-invariance of the heat kernel measure). *The heat kernel measure,  $\nu_T$ , is also quasi-invariant under right translations, and*

$$(6.5) \quad \frac{d\nu_T \circ r_k^{-1}}{d\nu_T}(g) = \bar{Z}_{k^{-1}}(g^{-1}).$$

where

$$\bar{Z}_k = d\nu_T \circ l_k^{-1} / d\nu_T$$

is as in Theorem 6.1.

*Proof.* Recall from Corollary 4.9 that  $\nu_T$  is invariant under the inversion map,  $g \rightarrow g^{-1}$ . From this observation and Theorem 6.1 it follows that  $\nu_T$  is also quasi-invariant under right translations of elements of  $G_{CM}$ . In more detail, if  $k \in G_{CM}$  and  $f : G \rightarrow \mathbb{R}$  is a bounded measurable function, then

$$\begin{aligned} \int_G f(g \cdot k) d\nu_T(g) &= \int_G f(g^{-1} \cdot k) d\nu_T(g) = \int_G f((k^{-1}g)^{-1}) d\nu_T(g) \\ &= \int_G f(g^{-1}) \bar{Z}_{k^{-1}}(g) d\nu_T(g) = \int_G f(g) \bar{Z}_{k^{-1}}(g^{-1}) d\nu_T(g). \end{aligned}$$

Equation (6.5) is a consequence of this identity.  $\square$

Just like in the case of abstract Wiener spaces we have the following strong converses of Theorem 6.1 and Corollary 6.2.

**Proposition 6.3.** *Suppose that  $k \in G \setminus G_{CM}$  and  $T > 0$ , then  $\nu_T \circ l_k^{-1}$  and  $\nu_T$  are singular and  $\nu_T \circ r_k^{-1}$  and  $\nu_T$  are singular.*

*Proof.* Let  $k = (A, a) \in G \setminus G_{CM}$  with  $a \in \mathbf{C}$  and  $A \in W \setminus H$ . Given a measurable subset,  $V \subset W$ , we have

$$\nu_T(V \times \mathbf{C}) = P(B(T) \in V) =: \mu_T(V),$$

where  $\mu_T$  is Wiener measure on  $W$  with variance  $T$ . It is well known (see e.g. Corollary 2.5.3 in [8]) that if  $A \in W \setminus H$  that  $\mu_T(\cdot - A)$  is singular relative to  $\mu_T(\cdot)$ , i.e. we may partition  $W$  into two disjoint measurable sets,  $W_0$  and  $W_1$  such that  $\mu_T(W_0) = 1 = \mu_T(W_1 - A)$ . A simple computation shows for any  $V \subset W$  that

$$l_k^{-1}(V \times \mathbf{C}) = r_k^{-1}(V \times \mathbf{C}) = (V - A) \times \mathbf{C}.$$

Thus if we define  $G_i := W_i \times \mathbf{C}$  for  $i = 0, 1$ , we have that  $G$  is the disjoint union of  $G_0$  and  $G_1$  and  $\nu_T(G_0) = \mu_T(W_0) = 1$  while

$$\nu_T(r_k^{-1}(G_1)) = \nu_T(l_k^{-1}(G_1)) = \nu_T((W_1 - A) \times \mathbf{C}) = \mu_T(W_1 - A) = 1.$$

□

**Corollary 6.4** (Right heat kernel integration by parts). *Let  $k := (A, a) \in \mathfrak{g}_{CM}$  and suppose that  $f : G \rightarrow \mathbf{C}$  is a smooth function such that  $f$  and  $\hat{k}f$  are polynomially bounded. Then*

$$\mathbb{E} \left[ \left( \hat{k}f \right) (g(T)) \right] = \mathbb{E} [f(g(T)) z_k]$$

where  $\hat{k}f(g) := \frac{d}{ds} \Big|_0 f((sk)g)$  and

$$z_k := \frac{1}{T} \left[ \langle A, B(T) \rangle_H + \langle a, B_0(T) \rangle_{\mathbf{C}} - \int_0^T \langle \omega(B(t), A), dB_0(t) \rangle_{\mathbf{C}} \right].$$

Moreover, with  $\nu_T := \text{Law}(g(T))$ , the above formula gives,

$$\int_G \left( \hat{k}f \right) d\nu_T(g) = \int_G f(g) \bar{z}_k(g) d\nu_T(g),$$

where

$$(6.6) \quad \bar{z}_k(g(T)) := \mathbb{E}(z_k | \sigma(g(T))).$$

*Proof.* This is a special case of Corollary 5.6, with  $k(t) := \frac{t}{T}(A, a)$  and  $F(g) := f(g(T))$ . □

**Corollary 6.5** (Left heat kernel integration by parts). *Let  $k := (A, a) \in \mathfrak{g}_{CM}$  and suppose that  $f : G \rightarrow \mathbf{C}$  is a smooth function such that  $f$  and  $\tilde{k}f$  are polynomially bounded. Then*

$$\int_G \left( \tilde{k}f \right) d\nu_T(g) = \int_G f(g) \bar{z}_k^l(g) d\nu_T(g),$$

where  $\tilde{k}f(g) := \frac{d}{ds} \Big|_0 f(g(sk))$  and

$$(6.7) \quad \bar{z}_k^l(g) = -\bar{z}_k(g^{-1})$$

where  $\bar{z}_k$  is defined in Equation (6.6).

*Proof.* Let  $u(g) := f(g^{-1})$  so that  $f(g) = u(g^{-1})$ . Then

$$\left(\tilde{k}f\right)(g) = \frac{d}{ds}\Big|_0 f(g \cdot (sk)) = \frac{d}{ds}\Big|_0 u((-sk) \cdot g^{-1}) = -\left(\hat{k}u\right)(g^{-1}).$$

Therefore by Corollary 6.4 and two uses of Corollary 4.9 we find

$$\begin{aligned} \int_G \left(\tilde{k}f\right) d\nu_T(g) &= - \int_G \left(\hat{k}u\right)(g^{-1}) d\nu_T(g) = - \int_G \left(\hat{k}u\right)(g) d\nu_T(g) \\ &= - \int_G u(g) \bar{z}_k(g) d\nu_T(g) = - \int_G f(g^{-1}) \bar{z}_k(g) d\nu_T(g) \\ &= - \int_G f(g) \bar{z}_k(g^{-1}) d\nu_T(g). \end{aligned}$$

□

**Definition 6.6.** A **cylinder polynomial** is a cylinder function,  $f = F \circ \pi_P : G \rightarrow \mathbb{C}$ , where  $P \in \text{Proj}(W)$  and  $F$  is a real or complex polynomial function on  $PH \times \mathbb{C}$ .

**Corollary 6.7** (Closability of the Dirichlet Form). *Given real-valued cylindrical polynomials,  $u, v$  on  $G$ , let*

$$\mathcal{E}_T^0(u, v) := \int_G \langle \text{grad } u, \text{grad } v \rangle_H d\nu_T,$$

where  $\text{grad } u : G \rightarrow \mathfrak{g}_{CM}$  is the gradient of  $u$  defined by

$$\langle \text{grad } u, k \rangle_{\mathfrak{g}_{CM}} = \tilde{k}u \text{ for all } k \in \mathfrak{g}_{CM}.$$

Then  $\mathcal{E}_T^0$  is closable and its closure,  $\mathcal{E}_T$ , is a Dirichlet form on  $\text{Re } L^2(G, \nu_T)$ .

*Proof.* The closability of  $\mathcal{E}_T^0$  is equivalent to the closability of the gradient operator,  $\text{grad} : L^2(\nu_T) \rightarrow L^2(\nu_T) \otimes \mathfrak{g}_{CM}$ , with the domain,  $\mathcal{D}(\text{grad})$ , being the space of cylinder polynomials on  $G$ . To check the latter statement it suffices to show that  $\text{grad}$  has a densely defined adjoint which is easily accomplished. Indeed, if  $k \in \mathfrak{g}_{CM}$  and  $u$  and  $v$  are cylinder polynomials, then

$$\begin{aligned} \langle \text{grad } u, v \cdot k \rangle_{L^2(\nu_T) \otimes \mathfrak{g}_{CM}} &= \int_G \tilde{k}u \cdot v d\nu_T \\ &= \int_G \left[ \tilde{k}(u \cdot v) - u \cdot \tilde{k}v \right] d\nu_T \\ &= \left\langle u, -\tilde{k}v + \bar{z}_k^l v \right\rangle_{L^2(\nu_T)}, \end{aligned}$$

wherein we have used the product rule in the second equality and Corollary 6.5 for the third. This shows that  $v \cdot k$  is contained in the domain of  $\text{grad}^*$  and  $\text{grad}^*(v \cdot k) = -\tilde{k}v + \bar{z}_k^l v$ , where  $z_k^l$  is as in Eq. (6.7). This completes the proof since linear combination of functions of the form  $v \cdot k$  with  $k \in \mathfrak{g}_{CM}$  and  $v$  being a cylinder polynomial is dense in  $L^2(\nu_T) \otimes \mathfrak{g}_{CM}$ . □

## 7. THE RICCI CURVATURE ON HEISENBERG TYPE GROUPS

In this section we compute the Ricci curvature for  $G(\omega)$  and its finite-dimensional approximations. This information will be used in Section 8 to prove a logarithmic Sobolev inequality for  $\nu_T$  and to get detailed  $L^p$ -bounds on the Radon-Nikodym derivatives of  $\nu_T$  under translations by elements from  $G_{CM}$ .



**Notation 7.1.** Let  $(W, H, \omega)$  be as in Notation 3.1,  $P \in \text{Proj}(W)$ , and  $G_P = PW \times \mathbf{C} \subset G_{CM}$  as in Notation 3.24. We equip  $G_P$  with the left invariant Riemannian metric induced from restriction of the (real part of the) inner product on  $\mathfrak{g}_{CM} = H \times \mathbf{C}$  to  $\text{Lie}(G_P) = PH \times \mathbf{C}$ . Further, let  $\text{Ric}^P$  denote the associated Ricci tensor at the identity in  $G_P$ .

**Proposition 7.2.** If  $(W, H, \omega, P)$  as in Notation 7.1,  $P \in \text{Proj}(W)$  is as in Eq. (3.42), and  $(A, a) \in PH \times \mathbf{C}$ , then

(7.1)

$$\begin{aligned} \langle \text{Ric}^P(A, a), (A, a) \rangle_{H \times \mathbf{C}} &= \frac{1}{4} \sum_{j,k=1}^n |\langle \omega(e_k, e_j), a \rangle_{\mathbf{C}}|^2 - \frac{1}{2} \sum_{k=1}^n \|\omega(A, e_k)\|_{\mathbf{C}}^2 \\ (7.2) \quad &= \frac{1}{4} \|\langle \omega(\cdot, \cdot), a \rangle_{\mathbf{C}}\|_{(PH)^* \otimes (PH)^*}^2 - \frac{1}{2} \|\omega(A, \cdot)\|_{(PH)^* \otimes \mathbf{C}}^2. \end{aligned}$$

*Proof.* We are going to compute  $\text{Ric}^P$  using the formula in Equation (B.3) of Appendix B. If  $\{f_\ell\}_{\ell=1}^{\dim \mathbf{C}}$  is an orthonormal basis for  $\mathbf{C}$ , then

$$(7.3) \quad \sum_{k=1}^n \|ad_{(e_k, 0)}(A, a)\|_{H \times \mathbf{C}}^2 + \sum_{\ell=1}^{\dim \mathbf{C}} \|ad_{(0, f_\ell)}(A, a)\|_{H \times \mathbf{C}}^2 = \sum_{k=1}^n \|\omega(e_k, A)\|_{\mathbf{C}}^2.$$

If  $(B, b) \in PH \times \mathbf{C}$ , then

$$\begin{aligned} ad_{(B, b)}^*(A, a) &= \sum_{j=1}^n \left\langle ad_{(B, b)}^*(A, a), (e_j, 0) \right\rangle_{\mathfrak{g}_{CM}} (e_j, 0) \\ &\quad + \sum_{\ell=1}^{\dim \mathbf{C}} \left\langle ad_{(B, b)}^*(A, a), (0, f_\ell) \right\rangle_{\mathfrak{g}_{CM}} (0, f_\ell) \\ &= \sum_{j=1}^n \langle (A, a), [(B, b), (e_j, 0)] \rangle_{\mathfrak{g}_{CM}} (e_j, 0) \\ &\quad + \sum_{\ell=1}^{\dim \mathbf{C}} \langle (A, a), [(B, b), (0, f_\ell)] \rangle_{\mathfrak{g}_{CM}} (0, f_\ell) \\ &= \sum_{j=1}^n \langle (A, a), (0, \omega(B, e_j)) \rangle_{\mathfrak{g}_{CM}} (e_j, 0) = \sum_{j=1}^n (a, \omega(B, e_j))_{\mathbf{C}} (e_j, 0). \end{aligned}$$

This then immediately implies

(7.4)

$$\sum_{k=1}^n \|ad_{(e_k, 0)}^*(A, a)\|_{\mathfrak{g}_{CM}}^2 + \sum_{\ell=1}^{\dim \mathbf{C}} \|ad_{(0, f_\ell)}^*(A, a)\|_{\mathfrak{g}_{CM}}^2 = \sum_{k=1}^n \sum_{j=1}^n \langle a, \omega(e_k, e_j) \rangle_{\mathbf{C}}^2.$$

Using Equations (7.3) and (7.4) with the formula for the Ricci tensor in Equation (B.3) of Appendix B implies Equation (7.1).  $\square$

**Corollary 7.3.** For  $P \in \text{Proj}(W)$  as in (3.42), let

$$(7.5) \quad k_P(\omega) := -\frac{1}{2} \sup \left\{ \|\omega(\cdot, A)\|_{(PH)^* \otimes \mathbf{C}}^2 : A \in PH, \|A\|_{PH} = 1 \right\}.$$

Also let

$$(7.6) \quad k(\omega) := -\frac{1}{2} \sup_{\|A\|_H=1} \|\omega(\cdot, A)\|_{H^* \otimes \mathbf{C}}^2 \geq -\frac{1}{2} \|\omega\|_2^2 > -\infty.$$

Then  $k_P(\omega)$  is the largest constant  $k \in \mathbb{R}$  such that

$$(7.7) \quad \langle \text{Ric}^P(A, a), (A, a) \rangle_{PH \times \mathbf{C}} \geq k \|(A, a)\|_{PH \times \mathbf{C}}^2 \quad \text{for all } (A, a) \in PH \times \mathbf{C}$$

and  $k(\omega)$  is the largest constant  $k \in \mathbb{R}$  such that Equation (7.7) holds uniformly for all  $P \in \text{Proj}(W)$ .

*Proof.* Let us observe that by Equation (7.1)

$$\frac{\langle \text{Ric}^P(A, a), (A, a) \rangle_{PH \times \mathbf{C}}}{\|(A, a)\|_{PH \times \mathbf{C}}^2} \geq \frac{\langle \text{Ric}^P(A, 0), (A, 0) \rangle_{PH \times \mathbf{C}}}{\|(A, 0)\|_{PH \times \mathbf{C}}^2}$$

the optimal lower bound,  $k_P(\omega)$ , for  $\text{Ric}^P$  is determined by

$$\begin{aligned} k_P(\omega) &= \inf_{A \in PH \setminus \{0\}} \frac{\langle \text{Ric}^P(A, 0), (A, 0) \rangle_{PH \times \mathbf{C}}}{\|(A, 0)\|_{PH \times \mathbf{C}}^2} \\ &= \inf_{A \in PH \setminus \{0\}} \left( -\frac{1}{2} \frac{\|\omega(\cdot, A)\|_{(PH)^* \otimes \mathbf{C}}^2}{\|A\|_{PH}^2} \right) \end{aligned}$$

which is equivalent to Equation (7.5). It is now a simple matter to check that  $k(\omega) = \inf_{P \in \text{Proj}(W)} k_P(\omega)$  which is the content of the last assertion of the theorem.  $\square$

In revisiting the examples from Section 3.3 we will have a number of cases where  $H$  and  $\mathbf{C}$  are complex Hilbert spaces and  $\omega : H \times H \rightarrow \mathbf{C}$  will be a complex bilinear form. In these cases it will be convenient to express the Ricci curvature in terms of these complex structures.

**Proposition 7.4.** *Suppose that  $H$  and  $\mathbf{C}$  are complex Hilbert spaces,  $\omega : H \times H \rightarrow \mathbf{C}$  is complex bi-linear, and  $P : H \rightarrow H$  is a finite rank (complex linear) orthogonal projection. We make  $G_P = PH \times \mathbf{C}$  into a Lie group using the group law in Equation (3.6). Let us endow  $G_P$  with the left invariant Riemannian metric which agrees with  $\langle \cdot, \cdot \rangle_{[\mathfrak{g}_P]_{\text{Re}}} := \text{Re} \langle \cdot, \cdot \rangle_{\mathfrak{g}_P}$  on  $\mathfrak{g}_P = PH \times \mathbf{C}$  at the identity in  $G_P$ . Then for all  $(A, a) \in \mathfrak{g}_P$ ,*

$$(7.8) \quad \begin{aligned} \langle \text{Ric}^P(A, a), (A, a) \rangle_{[\mathfrak{g}_P]_{\text{Re}}} &= \frac{1}{2} \|\langle \omega(\cdot, \cdot), a \rangle_{\mathbf{C}}\|_{(PH)^* \otimes (PH)^*}^2 - \|\omega(A, \cdot)\|_{(PH)^* \otimes \mathbf{C}}^2 \\ (7.9) \quad &= \frac{1}{2} \sum_{j,k=1}^n |\langle \omega(e_k, e_j), a \rangle_{\mathbf{C}}|^2 - \sum_{k=1}^n \|\omega(A, e_k)\|_{\mathbf{C}}^2, \end{aligned}$$

where  $\{e_j\}_{j=1}^n$  is any orthonormal basis for  $PH$ .

*Proof.* Applying Equation (7.2) with  $PH$ ,  $\mathbf{C}$ , and  $\mathfrak{g}_P$  being replaced by  $(PH)_{\text{Re}}$ ,  $\mathbf{C}_{\text{Re}}$ , and  $[\mathfrak{g}_P]_{\text{Re}}$  implies

$$\begin{aligned} \langle \text{Ric}^P(A, a), (A, a) \rangle_{[\mathfrak{g}_P]_{\text{Re}}} &= \frac{1}{4} \|\langle \omega(\cdot, \cdot), a \rangle_{\mathbf{C}_{\text{Re}}}\|_{(PH)_{\text{Re}}^* \otimes (PH)_{\text{Re}}^*}^2 \\ &\quad - \frac{1}{2} \|\omega(A, \cdot)\|_{(PH)_{\text{Re}}^* \otimes \mathbf{C}_{\text{Re}}}^2. \end{aligned}$$

However, by Lemma 3.17 we also know that

$$\|\langle \omega(\cdot, \cdot), a \rangle_{\mathbf{C}_{\text{Re}}}\|_{(PH)_{\text{Re}}^* \otimes (PH)_{\text{Re}}^*}^2 = 2 \|\langle \omega(\cdot, \cdot), a \rangle_{\mathbf{C}}\|_{(PH)^* \otimes (PH)^*}^2$$

and

$$\|\omega(A, \cdot)\|_{(PH)_{\text{Re}}^* \otimes \mathbf{C}_{\text{Re}}}^2 = 2 \|\omega(A, \cdot)\|_{(PH)^* \otimes \mathbf{C}}^2$$

which completes the proof of Equation (7.8).  $\square$

**Remark 7.5.** By letting  $n \rightarrow \infty$  in Propositions 7.2 and 7.4, it is reasonable to interpret the Ricci tensor on  $G_{CM}$  to be determined by

(7.10)

$$\begin{aligned} \langle \text{Ric}(A, a), (A, a) \rangle_{[\mathfrak{g}_{CM}]_{\text{Re}}} &= \alpha_{\mathbb{F}} \left( \frac{1}{4} \|\langle a, \omega(\cdot, \cdot) \rangle_{\mathbf{C}}\|_{H^* \otimes H^*}^2 - \frac{1}{2} \|\omega(\cdot, A)\|_{H^* \otimes \mathbf{C}}^2 \right) \\ (7.11) \quad &= \alpha_{\mathbb{F}} \left( \frac{1}{4} \sum_{j,k=1}^{\infty} |\langle a, \omega(e_k, e_j) \rangle_{\mathbf{C}}|^2 - \frac{1}{2} \sum_{k=1}^{\infty} \|\omega(e_k, A)\|_{\mathbf{C}}^2 \right), \end{aligned}$$

where  $\{e_j\}_{j=1}^{\infty}$  is an orthonormal basis for  $H$ ,  $\mathbb{F}$  is either  $\mathbb{R}$  or  $\mathbb{C}$  and  $\alpha_{\mathbb{F}}$  is one or two respectively. Moreover if  $\mathbf{C} = \mathbb{F}$ , then Equation (7.10) may be written as

$$(7.12) \quad \langle \text{Ric}(A, a), (A, a) \rangle_{[\mathfrak{g}_{CM}]_{\text{Re}}} = \alpha_{\mathbb{F}} \left( \frac{1}{4} \|\omega(\cdot, \cdot)\|_{H^* \otimes H^*}^2 \cdot |a|^2 - \frac{1}{2} \|\omega(\cdot, A)\|_{H^*}^2 \right).$$

**7.1. Examples revisited.** Using Equation (7.10), it is straightforward to compute the Ricci tensor on  $G$  for each of the Examples 3.18 – 3.23.

**Lemma 7.6.** *The Ricci tensor for  $G_{CM}$  associated to each of the structures introduced in Examples 3.18 and 3.19 are given (respectively) by*

$$(7.13) \quad \langle \text{Ric}(z, c), (z, c) \rangle_{\mathfrak{h}_{\mathbb{R}}^n} = \frac{nc^2}{2} - \frac{1}{2} \|z\|_{\mathbb{C}^n}^2 \quad \text{for all } (z, c) \in \mathbb{C}^n \times \mathbb{R},$$

and

$$(7.14) \quad \langle \text{Ric}(z, c), (z, c) \rangle_{[\mathfrak{h}_{\mathbb{C}}^n]_{\text{Re}}} = n|c|^2 - \|z\|_{\mathbb{C}^{2n}}^2 \quad \text{for all } (z, c) \in \mathbb{C}^{2n} \times \mathbb{C}.$$

*Proof.* We omit the proof of this lemma as it can be deduced from the next proposition by taking  $Q = I$ .  $\square$

**Proposition 7.7.** *The Ricci tensor for  $G_{CM}$  associated to each of the structures introduced in Examples 3.20 and 3.21 are given (respectively) by*

$$(7.15) \quad \langle \text{Ric}(h, c), (h, c) \rangle_{\mathfrak{g}_{CM}} = \frac{1}{2} \left[ c^2 \text{tr } Q^2 - \|Qh\|_H^2 \right] \quad \text{for all } (h, c) \in H \times \mathbb{R},$$

and

$$(7.16) \quad \langle \text{Ric}(k_1, k_2, c), (k_1, k_2, c) \rangle_{[\mathfrak{g}_{CM}]_{\text{Re}}} = |c|^2 \text{tr } Q^2 - \|Qk_1\|_K^2 - \|Qk_2\|_K^2$$

for all  $(k_1, k_2, c) \in K \times K \times \mathbb{R}$ .

*Proof.* We start with the proof of Equation (7.15). In this case,

$$\|\omega(\cdot, h)\|_{H_{\text{Re}}^*}^2 = \sum_{j=1}^{\infty} \left[ \omega(e_j, A)^2 + \omega(ie_j, A)^2 \right]$$

$$\begin{aligned}
&= \sum_{j=1}^{\infty} \left[ \left( \operatorname{Im} \langle h, e_j \rangle_Q \right)^2 + \left( \operatorname{Im} \langle h, ie_j \rangle_Q \right)^2 \right] \\
&= \sum_{j=1}^{\infty} \left[ \left( \operatorname{Im} \langle h, e_j \rangle_Q \right)^2 + \left( \operatorname{Re} \langle h, e_j \rangle_Q \right)^2 \right] \\
&= \sum_{j=1}^{\infty} \left| \langle h, e_j \rangle_Q \right|^2 = \|Qh\|_H^2
\end{aligned}$$

and from Equation (3.36)  $\|\omega\|_2^2 = 2 \operatorname{tr} (Q^2)$ . Using these results in Equation (7.12) with  $\mathbb{F} = \mathbb{R}$  gives Equation (7.15) with  $\mathbb{F} = \mathbb{C}$  and  $H = K \times K$ , Equation (7.16) follows from Equation (7.12) with  $\mathbb{F} = \mathbb{C}$ , Equation (3.36), and the following identity;

$$\begin{aligned}
(7.17) \quad \|\omega((k_1, k_2), \cdot)\|_{H^*}^2 &= \sum_{j=1}^{\infty} \left( |\omega((k_1, k_2), (e_j, 0))|^2 + |\omega((k_1, k_2), (0, e_j))|^2 \right) \\
&= \sum_{j=1}^{\infty} |\langle k_2, Q\bar{e}_j \rangle|^2 + \sum_{j=1}^{\infty} |\langle k_1, Q\bar{e}_j \rangle|^2 \\
&= \|Qk_1\|_K^2 + \|Qk_2\|_K^2.
\end{aligned}$$

□

**Proposition 7.8.** *The Ricci tensor for  $G_{CM}$  associated to the structure introduced in Example 3.22 is given by*

$$(7.18) \quad \langle \operatorname{Ric}(v, c), (v, c) \rangle_{[\mathfrak{g}_{CM}]_{\operatorname{Re}}} = \sum_{j=1}^{\infty} q_j^2 \langle \operatorname{Ric}^\alpha(v_j, c), (v_j, c) \rangle_{V_{\operatorname{Re}} \times \mathbf{C}_{\operatorname{Re}}} \quad \forall (v, c) \in H \times \mathbb{F},$$

where  $\operatorname{Ric}^\alpha$  denotes the Ricci tensor on  $G(\alpha) := V \times \mathbf{C}$  as is defined by Equation (7.19) below.

*Proof.* Using Equation (3.38) along with the identity,

$$\begin{aligned}
\|\omega(\cdot, v)\|_{H^* \otimes \mathbf{C}}^2 &= \sum_{j=1}^{\infty} \sum_{a=1}^d \|\omega(u_a(j), v)\|_{\mathbf{C}}^2 = \sum_{j=1}^{\infty} \sum_{a=1}^d q_j^2 \|\alpha(u_a, v_j)\|_{\mathbf{C}}^2 \\
&= \sum_{j=1}^{\infty} q_j^2 \|\alpha(\cdot, v_j)\|_{V^* \otimes \mathbf{C}}^2,
\end{aligned}$$

in Equation (7.10) shows

$$\langle \operatorname{Ric}(v, c), (v, c) \rangle_{[\mathfrak{g}_{CM}]_{\operatorname{Re}}} = \alpha_{\mathbb{F}} \sum_{j=1}^{\infty} q_j^2 \left( \frac{1}{4} \|\langle \alpha(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_2^2 - \frac{1}{2} \|\alpha(\cdot, v_j)\|_{V^* \otimes \mathbf{C}}^2 \right).$$

Moreover, by a completely analogous finite-dimensional application of Equation (7.10), we have

$$(7.19) \quad \langle \operatorname{Ric}^\alpha(v_j, c), (v_j, c) \rangle_{V_{\operatorname{Re}} \times \mathbf{C}_{\operatorname{Re}}} = \alpha_{\mathbb{F}} \left( \frac{1}{4} \|\langle \alpha(\cdot, \cdot), c \rangle_{\mathbf{C}}\|_2^2 - \frac{1}{2} \|\alpha(\cdot, v_j)\|_{V^* \otimes \mathbf{C}}^2 \right).$$

Combining these two identities completes the proof. □

**Proposition 7.9.** *Let  $\alpha : V \times V \rightarrow \mathbf{C}$  be as in Example 3.23. For  $v \in V$ , let  $\alpha_v : V \rightarrow \mathbf{C}$  be defined by  $\alpha_v w = \alpha(v, w)$  and  $\alpha_v^* : \mathbf{C} \rightarrow V$  be its adjoint. The Ricci tensor for  $G_{CM}$  associated to the structure introduced in Example 3.23 is then given by*

$$(7.20) \quad \begin{aligned} \langle \text{Ric}(h, c), (h, c) \rangle_{[\mathfrak{g}_{CM}]_{\text{Re}}} &= \frac{1}{2} \left[ \int_{[0,1]^2} (s \wedge t)^2 d\eta(s) d\bar{\eta}(t) \right] \cdot \|\langle c, \alpha(\cdot, \cdot) \rangle_{\mathbf{C}}\|_{V^* \otimes V^*}^2 \\ &\quad - \int_{[0,1]^2} (s \wedge t) \text{tr} \left( \alpha_{h(t)}^* \alpha_{h(s)} \right) d\eta(s) d\bar{\eta}(t). \end{aligned}$$

*Proof.* In this example we have

$$\begin{aligned} \|\omega(h, \cdot)\|_{H^* \otimes \mathbf{C}}^2 &= \sum_{j=1}^{\infty} \sum_{a=1}^d \|\omega(h, l_j u_a)\|_{\mathbf{C}}^2 \\ &= \sum_{j=1}^{\infty} \sum_{a=1}^d \left\| \int_0^1 \alpha(h(s), l_j(s) u_a) d\eta(s) \right\|_{\mathbf{C}}^2 \\ &= \sum_{j=1}^{\infty} \sum_{a=1}^d \left\langle \int_0^1 \alpha(h(s), l_j(s) u_a) d\eta(s), \int_0^1 \alpha(h(t), l_j(t) u_a) d\eta(t) \right\rangle_{\mathbf{C}} \\ &= \int_0^1 d\eta(s) \int_0^1 d\bar{\eta}(t) (s \wedge t) \sum_{a=1}^d \langle \alpha_{h(s)} u_a, \alpha_{h(t)} u_a \rangle_{\mathbf{C}} \\ &= \int_{[0,1]^2} s \wedge t \left[ \text{tr} \left( \alpha_{h(t)}^* \alpha_{h(s)} \right) \right] d\eta(s) d\bar{\eta}(t). \end{aligned}$$

Using this identity along with Equation (3.40) in Equation (7.10) with  $\alpha_{\mathbb{F}} = \alpha_{\mathbf{C}} = 2$  implies Equation (7.20).  $\square$

## 8. HEAT INEQUALITIES

**8.1. Infinite-dimensional Radon-Nikodym derivative estimates.** Recall from Theorem 6.1 and Corollary 6.2, we have already shown that  $\nu_T \circ l_h^{-1}$  and  $\nu_T \circ r_h^{-1}$  are absolutely continuous to  $\nu_T$  for all  $h \in G_{CM}$  and  $T > 0$ . These results were based on the path space quasi-invariance formula given in Theorem 5.2. However, in light of the results in Malliavin [40] it is surprising that Theorem 5.2 holds at all and we do not expect it to extend to many other situations. Therefore, it is instructive to give an independent proof of Theorem 6.1 and Corollary 6.2 which will work for a much larger class of examples. The alternative proof have the added advantage of giving detailed size estimates on the resulting Radon-Nikodym derivatives.

**Theorem 8.1.** *For all  $h \in G_{CM}$  and  $T > 0$ ,  $\nu_T \circ l_h^{-1}$  and  $\nu_T \circ r_h^{-1}$  are absolutely continuous to  $\nu_T$ . Let  $Z_h^l := \frac{d(\nu_T \circ l_h^{-1})}{d\nu_T}$  and  $Z_h^r := \frac{d(\nu_T \circ r_h^{-1})}{d\nu_T}$  be the respective Radon-Nikodym derivatives,  $k(\omega)$  is given in Equation (7.6), and*

$$c(t) := \frac{t}{e^t - 1} \quad \text{for all } t \in \mathbb{R}$$

with the convention that  $c(0) = 1$ . Then for all  $1 \leq p < \infty$ ,  $Z_h^l$  and  $Z_h^r$  are both in  $L^p(\nu_T)$  and satisfy the estimate

$$(8.1) \quad \|Z_h^*\|_{L^p(\nu_T)} \leq \exp\left(\frac{c(k(\omega)T)(p-1)}{2T} d_{G_{CM}}^2(e, h)\right),$$

where  $*$  =  $l$  or  $*$  =  $r$ .

*Proof.* The proof of this theorem is an application of Theorem 7.3 and Corollary 7.4 in [18] on quasi-invariance of the heat kernel measures for inductive limits of finite-dimensional Lie groups. In applying these results the reader should take:  $G_0 = G_{CM}$ ,  $A = \text{Proj}(W)$ ,  $s_P := \pi_P$ ,  $\nu_P = \text{Law}(g_P(T))$ , and  $\nu = \nu_T = \text{Law}(g(T))$ . We now verify that the hypotheses [18, Theorem 7.3] are satisfied. These assumptions include a denseness condition on the inductive limit group, consistency of the heat kernel measures on finite-dimensional Lie groups, uniform bound on the Ricci curvature, and finally that the length of a path in the inductive limit group can be approximated by the lengths of paths in finite-dimensional groups.

- (1) By Proposition 3.10,  $\cup_{P \in \text{Proj}(W)} G_P$  is a dense subgroup of  $G_{CM}$ .
- (2) From Lemma 4.7, for any  $\{P_n\}_{n=1}^\infty \subset \text{Proj}(W)$  with  $P_n|_H \uparrow I_H$  and  $f \in BC(G, \mathbb{R})$  (the bounded continuous maps from  $G$  to  $\mathbb{R}$ ), we have

$$\int_G f d\nu = \lim_{n \rightarrow \infty} \int_{G_{P_n}} (f \circ i_P) d\nu_{P_n}.$$

- (3) Corollary 7.3 shows that  $\text{Ric}_P \geq k(\omega) g_P$  for all  $P \in \text{Proj}(W)$ .
- (4) Lastly we have to verify that for any  $P_0 \in \text{Proj}(W)$ , and  $k \in C^1([0, 1], G_{CM})$  with  $k(0) = e$ , there exists an increasing sequence,  $\{P_n\}_{n=1}^\infty \subset \text{Proj}(W)$  such that  $P_0 \subset P_n$ ,  $P_n \uparrow I$  on  $H$ , and

$$(8.2) \quad \ell_{G_{CM}}(k) = \lim_{n \rightarrow \infty} \ell_{G_{P_n}}(\pi_n \circ k),$$

where  $\pi_n := \pi_{P_n}$  and  $\ell_{G_{CM}}(k)$  is the length of  $k$  (see Notation 3.9 with  $T = 1$ ). However, with  $k(t) = (A(t), c(t))$ , using the dominated convergence theorem applied to the identity (see Equation (3.21));

$$\begin{aligned} \ell_{G_{P_n}}(\pi_n \circ k) &= \int_0^1 \left\| \pi_n \dot{k}(t) - \frac{1}{2} [\pi_n k(t), \pi_n \dot{k}(t)] \right\|_{\mathfrak{g}_{CM}} dt \\ &= \int_0^1 \sqrt{\left\| P_n \dot{A}(t) \right\|_H^2 + \left\| \dot{c}(t) - \frac{1}{2} \omega(P_n A(t), P_n \dot{A}(t)) \right\|_C^2} dt \end{aligned}$$

shows Equation (8.2) holds for any such choice of  $P_n|_H \uparrow I_H$  with  $P_0 \subset P_n \in \text{Proj}(W)$ . □

**Remark 8.2.** In the case of infinite-dimensional matrix groups three out of four assumptions hold as has been shown in [24]. The condition that fails is the uniform bounds on the Ricci curvature which is one of the main results in [25].

## 8.2. Logarithmic Sobolev Inequality.

**Theorem 8.3.** *Let  $(\mathcal{E}_T, \mathcal{D}(\mathcal{E}_T))$  be the closed Dirichlet form in Corollary 6.7 and  $k(\omega)$  be as in Equation (7.6). Then for all real-valued  $f \in \mathcal{D}(\mathcal{E}_T)$ , the following*

logarithmic Sobolev inequality holds

$$(8.3) \quad \int_G (f^2 \ln f^2) d\nu_T \leq 2 \frac{1 - e^{-k(\omega)T}}{k(\omega)} \mathcal{E}_T(f, f) + \int_G f^2 d\nu_T \cdot \ln \int_G f^2 d\nu_T,$$

where  $\nu_T = \text{Law}(g(T))$  is the heat kernel measure on  $G$  as in Definition 4.2.

*Proof.* Let  $f : G \rightarrow \mathbb{R}$  be a cylinder polynomial as in Definition 6.6. Following the method of Bakry and Ledoux applied to  $G_P$  (see [22, Theorem 2.9] for the case needed here) shows

$$(8.4) \quad \begin{aligned} \mathbb{E} [(f^2 \log f^2)(g_P(T))] &\leq 2 \frac{1 - e^{-k_P(\omega)T}}{k_P(\omega)} \mathbb{E} \|(\text{grad}^P f)(g_P(T))\|_{G_P}^2 \\ &\quad + \mathbb{E} [f^2(g_P(T))] \log \mathbb{E} [f^2(g_P(T))] \end{aligned}$$

where  $k_P(\omega)$  is as in Equation (7.6). Since the function,  $x \rightarrow x^{-1}(1 - e^{-x})$ , is decreasing and  $k(\omega) \leq k_P(\omega)$  for all  $P \in \text{Proj}(W)$ , Equation (8.4) also holds with  $k_P(\omega)$  replaced by  $k(\omega)$ . With this observation along with Lemma 4.7, we may pass to the limit at  $P \uparrow I$  in Equation (8.4) to find

$$\begin{aligned} \mathbb{E} [(f^2 \log f^2)(g(T))] &\leq 2 \frac{1 - e^{-k(\omega)T}}{k(\omega)} \mathbb{E} |\text{grad} f(g(T))|^2 \\ &\quad + \mathbb{E} [f^2(g(T))] \log \mathbb{E} [f^2(g(T))]. \end{aligned}$$

This is equivalent to Equation (8.3) when  $f$  is a cylinder polynomial. The result for general  $f \in \mathcal{D}(\mathcal{E}_T)$  then holds by a standard (and elementary) limiting argument – see the end of Example 2.7 in [29].  $\square$

## 9. FUTURE DIRECTIONS

In this last section we wish to speculate on a number of ways that the results in this paper might be extended.

- (1) It would be interesting to see what happens if we set  $B_0$  to be identically zero so that  $g(t)$  in Equation (4.2) becomes

$$(9.1) \quad g(t) = \left( B(t), \frac{1}{2} \int_0^t \omega(B(\tau), \dot{B}(\tau)) d\tau \right).$$

The generator now is  $L = \frac{1}{2} \sum_{k=1}^{\infty} \widetilde{(e_k, 0)}^2$  and if  $\omega(\mathfrak{g}_{CM} \times \mathfrak{g}_{CM})$  is a total subset of  $\mathbf{C}$ ,  $L$  would satisfy Hörmander's condition for hypoellipticity. If  $\dim H$  were finite, it would follow that the heat kernel measure,  $\nu_T$ , is a smooth positive measure and hence quasi-invariant. When  $\dim H$  is infinite we do not know if  $\nu_T$  is still quasi-invariant. Certainly both proofs which were given above when  $B_0$  was not zero now break down.

- (2) It should be possible to remove the restriction on  $\mathbf{C}$  being finite-dimensional, i.e. we expect much of what we have done to go through when  $\mathbf{C}$  is a separable Hilbert space. In doing so one would have to modify the finite-dimensional approximations used in the theory to truncate  $\mathbf{C}$  as well.
- (3) It should be possible to widen the class of admissible  $\omega$ s substantially. The idea is to assume that  $\omega$  is only defined from  $H \times H \rightarrow \mathbf{C}$  such that  $\|\omega\|_2 < \infty$ . Under this relaxed assumption, we will no longer have a group

structure on  $G := W \times \mathbf{C}$ . Nevertheless, with a little work one can still make sense of Brownian motion process defined in Definition 4.2 by letting

$$(9.2) \quad \int_0^t \omega(B(\tau), dB(\tau)) := L^2 - \lim_{n \rightarrow \infty} \int_0^t \omega(P_n B(\tau), dP_n B(\tau)).$$

In fact, using Nelson's hypercontractivity and the fact that

$$\int_0^t \omega(P_n B(\tau), dP_n B(\tau))$$

is in the second homogeneous chaos subspace, the convergence in Equation (9.2) is in  $L^p$  for all  $p \in [1, \infty)$ . In this setting we expect the path space quasi-invariance results of Section 5 to remain valid. Similarly, as the lower bound on the Ricci curvature only depends on  $\omega|_{H \times H}$ , we expect the results of Section 8.1 to go through as well. As a consequence,  $G$  should carry a measurable left and right actions by element of  $G_{CM}$  and these actions should leave the heat kernel measures (end point distributions of the Brownian motion on  $G$ ) quasi-invariant. One might call the resulting structure a **quasigroup**. Unfortunately, this term has already been used in abstract algebra.

- (4) We also expect that level of non-commutativity of  $G$  may be increased. To be more precise, under suitable hypotheses, it should be possible to handle more general graded nilpotent Lie groups. However, when the level of nilpotency of  $G$  is increased, there will likely be trouble with the path space quasi-invariance in section 5. Nevertheless, the methods of Section 8.1 should survive and therefore we still expect the heat kernel measure to be quasi-invariant.

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#### APPENDIX A. WIENER SPACE RESULTS

The well known material presented in this Appendix may be (mostly) found in the books [36] and [8]. In particular, the following theorem is based in part on Lemma 2.4.1 on p. 59 of [8], and Theorem 3.9.6 on p. 138 [8].

**Theorem A.1.** *Let  $(X, \mathcal{B}_X, \mu)$  be a Gaussian measure space as in Definition 2.1. Then*

- (1)  $(H, \|\cdot\|_H)$  is a normed space such that

$$(A.1) \quad \|h\|_X \leq \sqrt{C_2} \|h\|_H \quad \text{for all } h \in H,$$

where  $C_2$  is as in (2.2).

- (2) Let  $K$  be the closure of  $X^*$  in  $\text{Re } L^2(\mu)$  and for  $f \in K$  let

$$\iota f := h_f := \int_X x f(x) d\mu(x) \in X,$$

where the integral is to be interpreted as a Bochner integral. Then  $\iota(K) = H$  and  $\iota : K \rightarrow H$  is an isometric isomorphism of real Banach spaces. Since  $K$  is a real Hilbert space it follows that  $\|\cdot\|_H$  is a Hilbertian norm on  $H$ .



(3)  $H$  is a separable Hilbert space and

$$(A.2) \quad (\iota u, h)_H = u(h) \text{ for all } u \in X^* \text{ and } h \in H.$$

(4) The Cameron-Martin space,  $H$ , is dense in  $X$ .

(5) The quadratic form  $q$  may be computed as

$$(A.3) \quad q(u, v) = \sum_{i=1}^{\infty} u(e_i)v(e_i)$$

where  $\{e_i\}_{i=1}^{\infty}$  is any orthonormal basis for  $H$ .

Notice that by Item 1.  $H \xrightarrow{i} X$  is continuous and hence so is  $X^* \xrightarrow{i^{tr}} H^* \cong H = (\cdot, \cdot)_{H^*}$ . Equation (A.3) asserts that

$$q = (\cdot, \cdot)_{H^*} \Big|_{X^* \times X^*}.$$

*Proof.* 1. Using Equation (2.6) we find

$$\|h\|_X = \sup_{u \in X^* \setminus \{0\}} \frac{|u(h)|}{\|u\|_{X^*}} \leq \sup_{u \in X^* \setminus \{0\}} \frac{|u(h)|}{\sqrt{q(u, u)}/C_2} \leq \sqrt{C_2} \|h\|_H,$$

and hence if  $\|h\|_H = 0$  then  $\|h\|_X = 0$  and so  $h = 0$ . If  $h, k \in H$ , then for all  $u \in X^*$ ,  $|u(h)| \leq \|h\|_H \sqrt{q(u)}$  and  $|u(k)| \leq \|k\|_H \sqrt{q(u)}$  so that

$$|u(h+k)| \leq |u(h)| + |u(k)| \leq (\|h\|_H + \|k\|_H) \sqrt{q(u)}.$$

This shows  $h+k \in H$  and  $\|h+k\|_H \leq \|h\|_H + \|k\|_H$ . Similarly, if  $\lambda \in \mathbb{R}$  and  $h \in H$ , then  $\lambda h \in H$  and  $\|\lambda h\|_H = |\lambda| \|h\|_H$ . Therefore  $H$  is a subspace of  $W$  and  $(H, \|\cdot\|_H)$  is a normed space.

2. For  $f \in K$  and  $u \in X^*$

$$(A.4) \quad u(\iota f) = u \left( \int_X x f(x) d\mu(x) \right) = \int_X u(x) f(x) d\mu(x)$$

and hence

$$|u(\iota f)| \leq \|u\|_{L^2(\mu)} \|f\|_{L^2(\mu)} = \sqrt{q(u)} \|f\|_K$$

which shows that  $\iota f \in H$  and  $\|\iota f\|_H \leq \|f\|_K$ . Moreover, by choosing  $u_n \in X^*$  such that  $L^2(\mu) - \lim_{n \rightarrow \infty} u_n = f$ , we find

$$\lim_{n \rightarrow \infty} \frac{|u_n(\iota f)|}{\sqrt{q(u_n)}} = \lim_{n \rightarrow \infty} \frac{\left| \int_X u_n(x) f(x) d\mu(x) \right|}{\|u_n\|_{L^2(\mu)}} = \frac{\|f\|_{L^2(\mu)}^2}{\|f\|_{L^2(\mu)}} = \|f\|_{L^2(\mu)}$$

from which it follows  $\|\iota f\|_H = \|f\|_K$ . So we have shown that  $\iota : K \rightarrow H$  is an isometry. Let us now show that  $\iota(K) = H$ . Given  $h \in H$  and  $u \in X^*$  let  $\hat{h}(u) = u(h)$ . Since

$$\left| \hat{h}(u) \right| \leq |u(h)| \leq \sqrt{q(u)} \|h\|_H = \|u\|_{L^2(\mu)} \|h\|_H = \|u\|_K \|h\|_H$$

the functional  $\hat{h}$  extends continuously to  $K$ . We will continue to denote this extension by  $\hat{h} \in K^*$ . Since  $K$  is a Hilbert space, there exists  $f \in K$  such that

$$\hat{h}(u) = \int_X f(x) u(x) d\mu(x)$$

for all  $u \in X^*$  (and in fact all  $u \in K$ ). Thus we have, for all  $u \in X^*$ , that

$$u(h) = \int_X u(x)f(x)d\mu(x) = u\left(\int_X xf(x)d\mu(x)\right) = u(\iota f).$$

From this equation we conclude that  $h = \iota f$  and hence  $\iota(K) = H$ .

3.  $H$  is a separable since it is unitarily equivalent to  $K \subset L^2(X, \mathcal{B}, \mu)$  and  $L^2(X, \mathcal{B}, \mu)$  is separable. Suppose that  $u \in X^*$ ,  $f \in K$  and  $h = \iota f \in H$ . Then

$$\begin{aligned} (\iota u, h)_H &= (\iota u, \iota f)_H = (u, f)_K \\ &= \int_X u(x)f(x)d\mu(x) = u\left(\int_X xf(x)d\mu(x)\right) \\ &= u(\iota f) = u(h). \end{aligned}$$

4. For sake of contradiction, if  $H \subset X$  were not dense, then, by the Hahn–Banach theorem, there would exist  $u \in X^* \setminus \{0\}$  such that  $u(H) = 0$ . However from Equation (A.2), we would then have

$$q(u, u) = (\iota u, \iota u)_H = u(\iota u) = 0.$$

Because we have assumed that  $q$  to be an inner product on  $X^*$ ,  $u$  must be zero contrary to  $u$  being in  $X^* \setminus \{0\}$ .

5. Let  $\{e_i\}_{i=1}^\infty$  be an orthonormal basis for  $H$ , then for  $u, v \in X^*$ ,

$$\begin{aligned} q(u, v) &= (u, v)_K = (\iota u, \iota v)_H = \sum_{i=1}^\infty (\iota u, e_i)_H (e_i, \iota v)_H \\ &= \sum_{i=1}^\infty u(e_i)v(e_i) \end{aligned}$$

wherein the last equality we have again used Equation (A.2).  $\square$

## APPENDIX B. THE RICCI TENSOR ON A LIE GROUP

In this appendix we recall a formula for the Ricci tensor relative to a left invariant Riemannian metric,  $\langle \cdot, \cdot \rangle$ , on any finite-dimensional Lie Group,  $G$ . Let  $\nabla$  be the Levi-Civita covariant derivative on  $TG$ , for any  $X \in \mathfrak{g}$  let  $\tilde{X}(g) = l_{g*}X$  be the left invariant vector field on  $G$  such that  $\tilde{X}(e) = X$ , and for  $X, Y \in \mathfrak{g}$ , let  $D_X Y := \nabla_X \tilde{Y} \in \mathfrak{g}$ . Since  $\nabla_{\tilde{X}} \tilde{Y}$  is a left invariant vector field and  $(\nabla_{\tilde{X}} \tilde{Y})(e) = \nabla_X \tilde{Y} = D_X Y$ , we have the identity;  $\nabla_{\tilde{X}} \tilde{Y} = \widetilde{D_X Y}$ . Similarly the Ricci curvature tensor, Ric, (and more generally the full curvature tensor) is invariant under left translations, i.e.  $\text{Ric}_g = l_{g^{-1}*} \text{Ric}_e l_{g*}$  for all  $g \in G$ . Hence it suffices to compute the Ricci tensor at  $e \in G$ . We will abuse notation and simply write Ric for  $\text{Ric}_e$ .

**Proposition B.1** (The Ricci tensor on  $G$ ). *Continuing the notation above, for all  $X, Y \in \mathfrak{g}$  we have*

$$(B.1) \quad D_X Y := \frac{1}{2} ([X, Y] - ad_X^* Y - ad_Y^* X) \in \mathfrak{g},$$

where  $ad_X^*$  denotes the adjoint of  $ad_X$  relative to  $\langle \cdot, \cdot \rangle_e$ . We also have,

$$(B.2) \quad \langle \text{Ric} X, X \rangle = \text{tr}(ad_{ad_X^* X}) - \frac{1}{2} \text{tr}(ad_X^2) + \frac{1}{4} \sum_{Y \in \Gamma} |ad_Y^* X|^2 - \frac{1}{2} \sum_{Y \in \Gamma} |ad_Y X|^2,$$

where  $\Gamma \subset \mathfrak{g}$  is any orthonormal basis for  $\mathfrak{g}$ . In particular if  $\mathfrak{g}$  is nilpotent then  $\text{tr}(ad_{ad_X^*} X) = 0$  and  $\text{tr}(ad_X^2) = 0$  and therefore Equation (B.2) reduces to

$$(B.3) \quad \langle \text{Ric } X, X \rangle = \frac{1}{4} \sum_{Y \in \Gamma} |ad_Y^* X|^2 - \frac{1}{2} \sum_{Y \in \Gamma} |ad_Y X|^2 \geq -\frac{1}{2} \sum_{Y \in \Gamma} |ad_Y X|^2.$$

These results may be found in [7], see Lemma 7.27, Theorem 7.30, and Corollary 7.33 for the computations of the Levi-Civita covariant derivative, the curvature tensor, and the Ricci curvature tensor respectively.

### APPENDIX C. PROOF OF THEOREM 3.12

Before giving the proof of Theorem 3.12 it will be necessary to develop the notion Carnot-Carathéodory distance function,  $\delta$ , in this infinite dimensional context.

**Notation C.1.** Let  $T > 0$  and  $C_{HCM}^1$  denote the horizontal elements in  $C_{CM}^1$ , where  $g \in C_{CM}^1$  is **horizontal** iff  $l_{g(s)^{-1}*} g'(s) \in H \times \{0\}$  for all  $s$ . We then define,

$$\delta(x, y) = \inf \{ \ell_{G_{CM}}(g) : g \in C_{HCM}^1 \text{ such that } g(0) = x \text{ and } g(T) = y \}$$

with the infimum of the empty set is taken to be infinite.

Observe that  $\delta(x, y) \geq d_{CM}(x, y)$  for all  $x, y \in G_{CM}$ . The following theorem describes the behavior of  $\delta$ .

**Theorem C.2.** If  $\{\omega(A, B) : A, B \in H\}$  is a total subset of  $\mathbf{C}$ , then there exists  $c \in (0, 1)$  such that

$$(C.1) \quad c \left( \|A\|_H + \sqrt{\|a\|_{\mathbf{C}}} \right) \leq \delta(\mathbf{e}, (A, a)) \leq c^{-1} \left( \|A\|_H + \sqrt{\|a\|_{\mathbf{C}}} \right) \text{ for all } (A, a) \in \mathfrak{g}_{CM}.$$

*Proof.* Our proof will be modeled on the standard proof of this result in the finite dimensional context, see for example [50, 42]. The only thing we must be careful of is to avoid using any compactness arguments.

For any left invariant metric,  $d$ , (e.g.  $d = \delta$  or  $d = d_{CM}$ ) on  $G_{CM}$  we have

$$(C.2) \quad d(\mathbf{e}, xy) \leq d(\mathbf{e}, x) + d(x, xy) = d(\mathbf{e}, x) + d(\mathbf{e}, y) \quad \forall x, y \in G_{CM}.$$

Given any path  $g = (w, c) \in C_{CM}^1$  joining  $\mathbf{e}$  to  $(A, a)$ , we have from Eq. (3.20) that

$$\begin{aligned} \ell_{G_{CM}}(g) &= \int_0^1 \sqrt{\|w'(s)\|_H^2 + \|c'(s) - \omega(w(s), w'(s))/2\|_{\mathbf{C}}^2} ds \\ &\geq \int_0^1 \|w'(s)\|_H ds \geq \|A\|_H \end{aligned}$$

from which it follows that

$$(C.3) \quad \delta(\mathbf{e}, (A, a)) \geq d_{CM}(\mathbf{e}, (A, 0)) \geq \|A\|_H.$$

Since the path  $g(t) = (tA, 0)$  is horizontal and

$$\|A\|_H = \ell_{G_{CM}}(g) \geq \delta(\mathbf{e}, (A, 0)) \geq d_{CM}(\mathbf{e}, (A, 0)) \geq \|A\|_H$$

it follows that

$$(C.4) \quad \delta(\mathbf{e}, (A, 0)) = d(\mathbf{e}, (A, 0)) = \|A\|_H \text{ for all } A \in H.$$

Given  $A, B \in H$ , let  $\xi(t) = A \cos t + B \sin t$  for  $0 \leq t \leq 2\pi$  and

$$g(t) = \left( \xi(t) - A, \frac{1}{2} \int_0^t \omega \left( \xi(\tau) - A, \dot{\xi}(\tau) \right) d\tau \right)$$

so that  $l_{g(t)_*}^{-1} \dot{g}(t) = (\xi(t), 0)$ ,  $g(0) = \mathbf{e}$ , and

$$\begin{aligned} g(2\pi) &= \left( 0, \frac{1}{2} \int_0^{2\pi} \omega \left( \xi(\tau), \dot{\xi}(\tau) \right) d\tau \right) \\ &= \left( 0, \frac{1}{2} \int_0^{2\pi} \omega(A, B) d\tau \right) = (0, \pi\omega(A, B)). \end{aligned}$$

From this one horizontal curve we may conclude that

$$\begin{aligned} \delta(\mathbf{e}, (0, \pi\omega(A, B))) &\leq \ell_{G_{CM}}(g) = \int_0^{2\pi} \|-A \sin t + B \cos t\|_H dt \\ (C.5) \qquad \qquad \qquad &\leq 2\pi (\|A\|_H + \|B\|_H). \end{aligned}$$

Choose  $\{A_\ell, B_\ell\}_{\ell=1}^d \subset H$  such that  $\{\pi\omega(A_\ell, B_\ell)\}_{\ell=1}^d$  is a basis for  $\mathbf{C}$ . Let  $\{\varepsilon^\ell\}_{\ell=1}^d$  be the corresponding dual basis. Hence for any  $a \in \mathbf{C}$  we have

$$\begin{aligned} \delta(\mathbf{e}, (0, a)) &= \delta \left( \mathbf{e}, \prod_{\ell=1}^d (0, \varepsilon^\ell(a) \pi\omega(A_\ell, B_\ell)) \right) \\ &\leq \sum_{\ell=1}^d \delta(\mathbf{e}, (0, \varepsilon^\ell(a) \pi\omega(A_\ell, B_\ell))) \\ &= \sum_{\ell=1}^d \delta \left( \mathbf{e}, \left( 0, \pi\omega \left( \operatorname{sgn}(\varepsilon^\ell(a)) \sqrt{|\varepsilon^\ell(a)|} A_\ell, \sqrt{|\varepsilon^\ell(a)|} B_\ell \right) \right) \right) \\ &\leq 2\pi \sum_{\ell=1}^d \left( \left\| \sqrt{|\varepsilon^\ell(a)|} A_\ell \right\|_H + \left\| \sqrt{|\varepsilon^\ell(a)|} B_\ell \right\|_H \right), \end{aligned}$$

wherein we have used Eq. (C.2) for the first inequality and Eq. (C.5) for the second inequality. It now follows by simple estimates that

$$(C.6) \quad \delta(\mathbf{e}, (0, a)) \leq C_1 \sum_{\ell=1}^d \sqrt{|\varepsilon^\ell(a)|} \leq C_2 \sqrt{\sum_{\ell=1}^d |\varepsilon^\ell(a)|} \leq C(\omega) \sqrt{\|a\|_{\mathbf{C}}}.$$

for some constants  $C_1 \leq C_2 \leq C(\omega) < \infty$ . Combining Eqs. (C.2), (C.4), and (C.6) gives,

$$\begin{aligned} \delta(\mathbf{e}, (A, a)) &= \delta(\mathbf{e}, (A, 0)(0, a)) \\ (C.7) \qquad \qquad &\leq \delta(\mathbf{e}, (A, 0)) + \delta(\mathbf{e}, (0, a)) \leq \|A\|_H + C(\omega) \sqrt{\|a\|_{\mathbf{C}}}. \end{aligned}$$

To prove the analogous lower bound we will make use of the dilation homomorphisms defined for each  $\lambda > 0$  by  $\varphi_\lambda(w, c) = (\lambda w, \lambda^2 c)$  for all  $(w, c) \in \mathfrak{g}_{CM} = G_{CM}$ . One easily verifies that  $\varphi_\lambda$  is both a Lie algebra homomorphism on  $\mathfrak{g}_{CM}$  and a group homomorphism on  $G_{CM}$ . Using the homomorphism property it follows that

$$l_{\varphi_\lambda(g(t))_*}^{-1} \frac{d}{dt} \varphi_\lambda(g(t)) = \varphi_\lambda \left( l_{g(t)_*}^{-1} \dot{g}(t) \right)$$

and consequently; if  $g$  is any horizontal curve, then  $\varphi_\lambda \circ g$  is again horizontal and  $\ell_{G_{CM}}(\varphi_\lambda \circ g) = \lambda \ell_{G_{CM}}(g)$ . From these observations we may conclude that

$$(C.8) \quad \delta(\varphi_\lambda(x), \varphi_\lambda(y)) = \lambda \delta(x, y) \text{ for all } x, y \in G_{CM}.$$

By Proposition 3.10, we know there exists  $\varepsilon > 0$  and  $K < \infty$  such that

$$(C.9) \quad K\delta(\mathbf{e}, x) \geq Kd_{G_{CM}}(\mathbf{e}, x) \geq \|x\|_{\mathfrak{g}_{CM}} \text{ whenever } \|x\|_{\mathfrak{g}_{CM}} \leq \varepsilon.$$

For arbitrary  $x = (A, a) \in G_{CM}$ , choose  $\lambda > 0$  such that

$$\varepsilon^2 = \|\varphi_\lambda(x)\|^2 = \lambda^2 \|A\|_H^2 + \lambda^4 \|a\|_C^2,$$

i.e.

$$\lambda^2 = \frac{\sqrt{\|A\|_H^4 + 4\|a\|_C^2 \varepsilon^2} - \|A\|_H^2}{2\|a\|_C^2}.$$

It then follows from Eqs. (C.8) and (C.9) that  $\lambda K\delta(\mathbf{e}, x) = K\delta(\mathbf{e}, \varphi_\lambda(x)) \geq \varepsilon$ , i.e.

$$(C.10) \quad \begin{aligned} \delta^2(\mathbf{e}, x) &\geq \frac{\varepsilon^2}{K^2 \lambda^2} = 2 \frac{\varepsilon^2}{K^2} \frac{\|a\|_C^2}{\sqrt{\|A\|_H^4 + 4\|a\|_C^2 \varepsilon^2} - \|A\|_H^2} \\ &= 2 \frac{\varepsilon^2 \|a\|_C^2}{K^2 \|A\|_H^2} \frac{1}{\sqrt{1 + \frac{4\|a\|_C^2 \varepsilon^2}{\|A\|_H^4}} - 1}. \end{aligned}$$

Since  $\sqrt{1+x} - 1 \leq \min(x/2, \sqrt{x})$  we have

$$\frac{1}{\sqrt{1+x} - 1} \geq \max\left(\frac{2}{x}, \frac{1}{\sqrt{x}}\right) \geq \frac{1}{x} + \frac{1}{2\sqrt{x}}.$$

Using this estimate with  $x = 4\|a\|_C^2 \|A\|_H^{-4} \varepsilon^2$  in Eq. (C.10) shows

$$\delta^2(\mathbf{e}, x) \geq 2 \frac{\varepsilon^2 \|a\|_C^2}{K^2 \|A\|_H^2} \left( \frac{\|A\|_H^4}{4\|a\|_C^2 \varepsilon^2} + \frac{\|A\|_H^2}{4\varepsilon \|a\|_C} \right) = \frac{1}{2K^2} \left( \|A\|_H^2 + \varepsilon \|a\|_C \right),$$

which implies the lower bound in Eq. (C.1).  $\square$

We are now ready to give the proof of Theorem 3.12

### C.1. Proof of Theorem 3.12.

*Proof.* The first assertion in Eq. (3.24) of Theorem 3.12 follows from Theorem C.2 and the previously observed fact that  $d_{CM} \leq \delta$ . To prove Eq. (3.25), let  $\varepsilon_0 < \varepsilon/2$  where  $\varepsilon > 0$  is as in Proposition 3.10. Then according to that proposition, if  $d_{CM}(\mathbf{e}, x) \leq \varepsilon_0$  then  $\|x\|_{\mathfrak{g}_{CM}} \leq Kd_{CM}(\mathbf{e}, x) \leq K\varepsilon_0$ . So if  $x = (A, a)$ , we have  $\|A\|_H \leq K\varepsilon_0$  and  $\|a\|_C \leq K\varepsilon_0$  and hence by Theorem C.2,  $\delta(\mathbf{e}, x) \leq c^{-1}(K\varepsilon_0 + \sqrt{K\varepsilon_0})$ . This implies that

$$(C.11) \quad M(\varepsilon_0) := \sup\{\delta(\mathbf{e}, x) : x \ni d_{CM}(\mathbf{e}, x) \leq \varepsilon_0\} \leq c^{-1}(K\varepsilon_0 + \sqrt{K\varepsilon_0}) < \infty.$$

Now suppose that  $x \in G_{CM}$  with  $d_{CM}(\mathbf{e}, x) \geq \varepsilon_0$ . Choose a curve,  $g \in C_{CM}^1$  such that  $g(0) = \mathbf{e}$ ,  $g(1) = x$ , and  $\ell_{G_{CM}}(g) \leq d_{CM}(\mathbf{e}, x) + \varepsilon_0/4$ . Also choose  $\varepsilon_1 \in (\varepsilon_0/2, \varepsilon_0]$  such that  $\ell_{G_{CM}}(g) = n\varepsilon_1$  with  $n \in \mathbb{N}$  and let  $0 = t_0 < t_1 < t_2 < \dots < t_n = 1$  be a partition of  $[0, 1]$  such that  $\ell_{G_{CM}}(g|_{[t_{i-1}, t_i]}) = \varepsilon_1$  for  $i = 1, 2, \dots, n$ . If  $x_i := g(t_i)$  for  $i = 0, \dots, n$ , then  $\varepsilon_0 \geq \varepsilon_1 = \ell_{G_{CM}}(g|_{[t_{i-1}, t_i]}) \geq d_{CM}(x_{i-1}, x_i)$

and therefore from Eq. (C.11) and the left invariance of  $d_{CM}$  and  $\delta$  we have  $1 \geq M(\varepsilon_0)^{-1} \delta(x_{i-1}, x_i)$  for  $i = 1, 2, \dots, n$ . Hence we may conclude that

$$\begin{aligned} 2d_{CM}(\mathbf{e}, x) &\geq d_{CM}(\mathbf{e}, x) + \varepsilon_0/4 \geq \ell_{G_{CM}}(g) = \varepsilon_1 n \\ &\geq \varepsilon_1 \sum_{i=1}^n M(\varepsilon_0)^{-1} \delta(x_{i-1}, x_i) \geq \frac{\varepsilon_0}{2} M(\varepsilon_0)^{-1} \delta(\mathbf{e}, x). \end{aligned}$$

Combining this estimate with the lower bound in Eq. (C.1) shows Eq. (3.25) holds for all  $\varepsilon_0$  sufficiently small which is enough to complete the proof.  $\square$

#### REFERENCES

- [1] Hélène Airault and Paul Malliavin, *Quasi-invariance of Brownian measures on the group of circle homeomorphisms and infinite-dimensional Riemannian geometry*, J. Funct. Anal. **241** (2006), no. 1, 99–142. MR MR2264248
- [2] D. Bakry, *On Sobolev and logarithmic Sobolev inequalities for Markov semigroups*, New trends in stochastic analysis (Charingworth, 1994), World Sci. Publ., River Edge, NJ, 1997, pp. 43–75. MR MR1654503 (99m:60110)
- [3] D. Bakry and M. Ledoux, *Lévy-Gromov’s isoperimetric inequality for an infinite-dimensional diffusion generator*, Invent. Math. **123** (1996), no. 2, 259–281. MR MR1374200 (97c:58162)
- [4] Denis Bell, *Divergence theorems in path space*, J. Funct. Anal. **218** (2005), no. 1, 130–149. MR MR2101217 (2005m:60120)
- [5] ———, *Divergence theorems in path space. II. Degenerate diffusions*, C. R. Math. Acad. Sci. Paris **342** (2006), no. 11, 869–872. MR MR2224638 (2007g:60059)
- [6] ———, *Quasi-invariant measures on the path space of a diffusion*, C. R. Math. Acad. Sci. Paris **343** (2006), no. 3, 197–200. MR MR2246431 (2007e:60080)
- [7] Arthur L. Besse, *Einstein manifolds*, Ergebnisse der Mathematik und ihrer Grenzgebiete (3) [Results in Mathematics and Related Areas (3)], vol. 10, Springer-Verlag, Berlin, 1987. MR MR867684 (88f:53087)
- [8] Vladimir I. Bogachev, *Gaussian measures*, Mathematical Surveys and Monographs, vol. 62, American Mathematical Society, Providence, RI, 1998. MR MR1642391 (2000a:60004)
- [9] R. H. Cameron and W. T. Martin, *Evaluation of various Wiener integrals by use of certain Sturm-Liouville differential equations*, Bull. Amer. Math. Soc. **51** (1945), 73–90. MR MR0011401 (6,160e)
- [10] Mireille Capitaine, Elton P. Hsu, and Michel Ledoux, *Martingale representation and a simple proof of logarithmic Sobolev inequalities on path spaces*, Electron. Comm. Probab. **2** (1997), 71–81 (electronic). MR MR1484557 (99b:60136)
- [11] G. DaPrato and J. Zabczyk, *Stochastic equations in infinite dimensions*, Encyclopedia of mathematics and its applications, Cambridge University Press, 1992.
- [12] E. B. Davies, *Heat kernels and spectral theory*, Cambridge Tracts in Mathematics, vol. 92, Cambridge University Press, Cambridge, 1989. MR MR990239 (90e:35123)
- [13] ———, *The state of the art for heat kernel bounds on negatively curved manifolds*, Bull. London Math. Soc. **25** (1993), no. 3, 289–292. MR MR1209255 (94f:58121)
- [14] J. Diestel and J. J. Uhl, Jr., *Vector measures*, American Mathematical Society, Providence, R.I., 1977, With a foreword by B. J. Pettis, Mathematical Surveys, No. 15. MR MR0453964 (56 #12216)
- [15] Jozef Dodziuk, *Maximum principle for parabolic inequalities and the heat flow on open manifolds*, Indiana Univ. Math. J. **32** (1983), no. 5, 703–716. MR MR711862 (85e:58140)
- [16] Bruce K. Driver, *Integration by parts and quasi-invariance for heat kernel measures on loop groups*, J. Funct. Anal. **149** (1997), no. 2, 470–547.
- [17] ———, *Heat kernels measures and infinite dimensional analysis*, Heat kernels and analysis on manifolds, graphs, and metric spaces (Paris, 2002), Contemp. Math., vol. 338, Amer. Math. Soc., Providence, RI, 2003, pp. 101–141. MR MR2039953
- [18] Bruce K. Driver and Maria Gordina, *Integrated Harnack inequalities on Lie groups*, preprint **tbd** (2007), 40 pages.
- [19] ———, *Square-integrable holomorphic functions on an infinite-dimensional Heisenberg type groups*, preprint (2008), 40+pp.

- [20] Bruce K. Driver and Leonard Gross, *Hilbert spaces of holomorphic functions on complex Lie groups*, New trends in stochastic analysis (Charingworth, 1994), World Sci. Publishing, River Edge, NJ, 1997, pp. 76–106. MR MR1654507 (2000h:46029)
- [21] Bruce K. Driver and Yaozhong Hu, *On heat kernel logarithmic Sobolev inequalities*, Stochastic analysis and applications (Powys, 1995), World Sci. Publ., River Edge, NJ, 1996, pp. 189–200. MR MR1453132 (98h:58183)
- [22] Bruce K. Driver and Terry Lohrenz, *Logarithmic Sobolev inequalities for pinned loop groups*, J. Funct. Anal. **140** (1996), no. 2, 381–448.
- [23] Patrick Eberlein, *Geometry of 2-step nilpotent Lie groups*, Modern dynamical systems and applications, Cambridge Univ. Press, Cambridge, 2004, pp. 67–101. MR MR2090766 (2005m:53081)
- [24] Maria Gordina, *Heat kernel analysis and Cameron-Martin subgroup for infinite dimensional groups*, J. Funct. Anal. **171** (2000), no. 1, 192–232.
- [25] ———, *Hilbert-Schmidt groups as infinite-dimensional Lie groups and their Riemannian geometry*, J. Funct. Anal. **227** (2005), no. 2, 245–272.
- [26] Alexander Grigor'yan, *Heat kernel of a noncompact Riemannian manifold*, Stochastic analysis (Ithaca, NY, 1993), Proc. Sympos. Pure Math., vol. 57, Amer. Math. Soc., Providence, RI, 1995, pp. 239–263. MR MR1335475 (96f:58155)
- [27] Leonard Gross, *Harmonic analysis on Hilbert space*, Mem. Amer. Math. Soc. No. **46** (1963), ii+62. MR MR0161095 (28 #4304)
- [28] ———, *Logarithmic Sobolev inequalities*, Amer. J. Math. **97** (1975), no. 4, 1061–1083. MR MR0420249 (54 #8263)
- [29] ———, *Logarithmic Sobolev inequalities and contractivity properties of semigroups*, Dirichlet forms (Varenna, 1992), Lecture Notes in Math., vol. 1563, Springer, Berlin, 1993, pp. 54–88. MR MR1292277 (95h:47061)
- [30] Elton P. Hsu, *Inégalités de Sobolev logarithmiques sur un espace de chemins*, C. R. Acad. Sci. Paris Sér. I Math. **320** (1995), no. 8, 1009–1012. MR MR1328728 (96e:58167)
- [31] Nobuyuki Ikeda and Shinzo Watanabe, *Stochastic differential equations and diffusion processes*, second ed., North-Holland Mathematical Library, vol. 24, North-Holland Publishing Co., Amsterdam, 1989. MR MR1011252 (90m:60069)
- [32] Yuzuru Inahama, *Logarithmic Sobolev inequality for  $H_0^s$ -metric on pinned loop groups*, Infin. Dimens. Anal. Quantum Probab. Relat. Top. **7** (2004), no. 1, 1–26. MR MR2021645 (2005d:58061)
- [33] M. Kac, *On some connections between probability theory and differential and integral equations*, Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability, 1950 (Berkeley and Los Angeles), University of California Press, 1951, pp. 189–215. MR MR0045333 (13,568b)
- [34] Olav Kallenberg, *Foundations of modern probability*, second ed., Probability and its Applications (New York), Springer-Verlag, New York, 2002. MR MR1876169 (2002m:60002)
- [35] Aroldo Kaplan, *Fundamental solutions for a class of hypoelliptic PDE generated by composition of quadratic forms*, Trans. Amer. Math. Soc. **258** (1980), no. 1, 147–153. MR MR554324 (81c:58059)
- [36] Hui Hsiung Kuo, *Gaussian measures in Banach spaces*, Springer-Verlag, Berlin, 1975, Lecture Notes in Mathematics, Vol. 463. MR MR0461643 (57 #1628)
- [37] Shigeo Kusuoka and Daniel W. Stroock, *Precise asymptotics of certain Wiener functionals*, J. Funct. Anal. **99** (1991), no. 1, 1–74. MR MR1120913 (93a:60085)
- [38] Michel Ledoux, *The geometry of Markov diffusion generators*, Ann. Fac. Sci. Toulouse Math. (6) **9** (2000), no. 2, 305–366, Probability theory. MR MR1813804 (2002a:58045)
- [39] Peter Li and Shing-Tung Yau, *On the parabolic kernel of the Schrödinger operator*, Acta Math. **156** (1986), no. 3–4, 153–201. MR MR834612 (87f:58156)
- [40] Paul Malliavin, *Hypoellipticity in infinite dimensions*, Diffusion processes and related problems in analysis, Vol. I (Evanston, IL, 1989), Progr. Probab., vol. 22, Birkhäuser Boston, Boston, MA, 1990, pp. 17–31. MR MR1110154 (93b:60132)
- [41] Michel Métivier, *Semimartingales*, de Gruyter Studies in Mathematics, vol. 2, Walter de Gruyter & Co., Berlin, 1982, A course on stochastic processes. MR MR688144 (84i:60002)
- [42] Richard Montgomery, *A tour of subriemannian geometries, their geodesics and applications*, Mathematical Surveys and Monographs, vol. 91, American Mathematical Society, Providence, RI, 2002. MR MR1867362 (2002m:53045)

- [43] Edward Nelson, *The free Markoff field*, J. Functional Analysis **12** (1973), 211–227. MR MR0343816 (49 #8556)
- [44] ———, *Quantum fields and Markoff fields*, Partial differential equations (Proc. Sympos. Pure Math., Vol. XXIII, Univ. California, Berkeley, Calif., 1971), Amer. Math. Soc., Providence, R.I., 1973, pp. 413–420. MR MR0337206 (49 #1978)
- [45] David Nualart, *The Malliavin calculus and related topics*, Probability and its Applications (New York), Springer-Verlag, New York, 1995. MR MR1344217 (96k:60130)
- [46] Laurent Saloff-Coste, *Uniformly elliptic operators on Riemannian manifolds*, J. Differential Geom. **36** (1992), no. 2, 417–450. MR MR1180389 (93m:58122)
- [47] ———, *Aspects of Sobolev-type inequalities*, London Mathematical Society Lecture Note Series, vol. 289, Cambridge University Press, Cambridge, 2002. MR MR1872526 (2003c:46048)
- [48] Robert S. Strichartz, *Analysis of the Laplacian on the complete Riemannian manifold*, J. Funct. Anal. **52** (1983), no. 1, 48–79. MR MR705991 (84m:58138)
- [49] Daniel W. Stroock, *Probability theory, an analytic view*, Cambridge University Press, Cambridge, 1993. MR MR1267569 (95f:60003)
- [50] N. Th. Varopoulos, L. Saloff-Coste, and T. Coulhon, *Analysis and geometry on groups*, Cambridge Tracts in Mathematics, vol. 100, Cambridge University Press, Cambridge, 1992. MR MR1218884 (95f:43008)
- [51] Feng-Yu Wang, *On estimation of the logarithmic Sobolev constant and gradient estimates of heat semigroups*, Probab. Theory Related Fields **108** (1997), no. 1, 87–101. MR MR1452551 (98h:58184)
- [52] Fengyu Wang, *Logarithmic Sobolev inequalities for diffusion processes with application to path space*, Chinese J. Appl. Probab. Statist. **12** (1996), no. 3, 255–264. MR MR1478794 (98j:60110)

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