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***L<sup>p</sup>*-cohomology for higher-rank spaces and groups:  
critical exponents and rigidity**

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# **$L^p$ -cohomology for higher-rank spaces and groups: critical exponents and rigidity**

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We initiate the investigation of critical exponents (in degree equal to the rank) for the vanishing of  $L^p$ -cohomology of higher-rank Lie groups and related manifolds. We deal with the rank 2 case and exhibit such phenomena for  $\mathrm{SL}_3(\mathbb{R})$  and for a family of 5-dimensional solvable Lie groups. We use the critical exponents to compare the groups up to quasi-isometry. This leads us to exhibit a continuum of quasi-isometry classes of rank 2 irreducible solvable Lie groups of nonpositive curvature. In the course of the proof, we provide a detailed description of the  $L^p$ -cohomology of the real and complex hyperbolic spaces. It is then combined with a spectral sequence argument, to derive our higher-rank results.

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## **Introduction**

**Overview**  $L^p$ -cohomology, with  $p \in (1, +\infty)$ , provides a family of large scale geometry invariants for metric spaces and groups. It has many incarnations (such as asymptotic  $L^p$ -cohomology, or group  $L^p$ -cohomology via continuous cohomology of locally compact groups), which are all comparable to one another under suitable, not so demanding, conditions. Each variant brings its own insights: for instance, asymptotic  $L^p$ -cohomology shows that  $L^p$ -cohomology is an invariant under quasi-isometry (in fact, under coarse isometry), and continuous cohomology allows one to use standard algebraic tools

such as spectral sequences. In the present paper, we are interested in the de Rham  $L^p$ -cohomology, which we denote by  $L^p H_{\text{dR}}^*$ . Roughly speaking, we are dealing with forms satisfying, together with their differentials,  $L^p$ -integrability conditions with respect to measures given by suitable Riemannian metrics.

For a general overview of  $L^p$ -cohomology we refer to the work of Gromov [1993]; for its invariance under quasi-isometry, see the work of Pansu [1995], Genton [2014] and Sequeira [2024]; for group  $L^p$ -cohomology, see the work of Elek [1998], Cornulier and Tessera [2011], Sauer and Schrödl [2018] and Bourdon and Rémy [2020]; for spectral sequences and applications, see the work of Bourdon and Rémy [2020; 2023] and Lopez Neumann [2023]; for de Rham  $L^p$ -cohomology of Lie groups see the work of Pansu [1999; 2007; 2008; 2011] and Sequeira [2024]. We also notice that [Bourdon and Rémy 2023, Section 6] contains a concise presentation of (some) of the several aspects of  $L^p$ -cohomology, as well as a description and comparison of their properties.

$L^p$ -cohomology of a (connected) Lie group is better understood in rank 1 situations,<sup>1</sup> when contractions and negative curvature arguments can be used to perform some computations. In particular, critical exponent phenomena with respect to  $p$  for vanishing vs nonvanishing of  $L^p$ -cohomology in degree 1 can be sometimes exhibited. An iconic example of this phenomenon is provided by the following family of solvable Lie groups: for  $\lambda \geq 1$ , let  $H_\lambda$  be the semidirect product  $H_\lambda = \mathbb{R} \ltimes_\lambda \mathbb{R}^2$ , where  $\mathbb{R}$  acts on  $\mathbb{R}^2$  via the 1-parameter group of automorphisms  $t \mapsto e^{-tA_\lambda}$ , with

$$A_\lambda = \begin{pmatrix} 1 & 0 \\ 0 & \lambda \end{pmatrix}.$$

When  $\lambda = 1$ , the group  $H_\lambda$  is naturally isometric to the real hyperbolic 3-space  $\mathbb{H}_{\mathbb{R}}^3$ . In general  $H_\lambda$  belongs to the family of the so-called *Heintze groups*, ie of the Lie groups that admit a left-invariant negatively curved Riemannian metric; see [Heintze 1974]. Pansu's theorem [2007] shows that  $L^p H_{\text{dR}}^1(H_\lambda)$  vanishes for  $p \in (1; 1 + \lambda)$ , and does not vanish for  $p > 1 + \lambda$ . In other words,  $1 + \lambda$  is a critical exponent of the first  $L^p$ -cohomology of  $H_\lambda$ . As a consequence, the groups  $H_\lambda$  are pairwise nonquasi-isometric. More generally, every Heintze group admits an explicit critical exponent in degree 1; see [Pansu 2007; Cornulier and Tessera 2011].

$L^p$ -cohomology of higher-rank Lie groups has attracted less attention so far. As a first step, it would be desirable to have a better understanding of  $L^p$ -cohomology in degree equal to the rank. Indeed, the first (reduced)  $L^p$ -cohomology of higher-rank Lie groups is known to vanish<sup>2</sup> for every  $p$ ; and vanishing for

<sup>1</sup>The *rank* of a Lie group is the dimension of its asymptotic cones; it is therefore a quasi-isometric invariant. For semisimple Lie groups, this notion coincides with the  $\mathbb{R}$ -rank. When the group is simply connected and solvable, its rank is equal to the codimension of its exponential radical [de Cornulier 2008, Corollary 1.3]. When the group admits a left-invariant Riemannian metric of nonpositive curvature, its rank is the same as the maximal dimension of a totally geodesic Euclidean subspace [Azencott and Wilson 1976]. We thank Yves Cornulier for providing us with this definition.

<sup>2</sup>More precisely, apart from those which are quasi-isometric to a Heintze group, the reduced first  $L^p$ -cohomology of every Lie group vanishes for every  $p$ , and the nonreduced one vanishes if, and only if, the group is nonamenable or nonunimodular [Pansu 2007; Cornulier and Tessera 2011].

every  $p$  is expected to remain true in any degree below the rank — at least for semisimple Lie groups, by [Gromov 1993, page 253] and [López Neumann 2023]. In degree equal to the rank, critical exponents are known to exist for several higher-rank real Lie groups, including all the semisimple ones [Bourdon and Rémy 2023]; but their values have not been determined yet.

In the present paper, we study the second  $L^p$ -cohomology of solvable Lie groups of rank 2. More precisely, we exhibit, for some groups of this type, a critical exponent in degree 2. We then use these critical exponents to derive a quasi-isometric rigidity result.

**A family of solvable Lie groups** We consider the solvable Lie groups of the form  $S_\alpha = \mathbb{R}^2 \ltimes_\alpha \mathbb{R}^3$ , where

$$\alpha: \mathbb{R}^2 \rightarrow \{\text{diagonal automorphisms of } \mathbb{R}^3\}$$

is a Lie group morphism. Let  $\varpi_i \in (\mathbb{R}^2)^*$  for  $i = 1, 2, 3$  denote the *weights* associated to  $\alpha$ , ie the linear forms such that  $\alpha = e^{\text{diag}(\varpi_1, \varpi_2, \varpi_3)}$ .

We shall let  $\mathcal{G}_{\text{straight}}^{2,3}$  denote the set of the groups  $S_\alpha$  whose weights enjoy the following two properties:

- they generate  $(\mathbb{R}^2)^*$ ,
- they belong to an affine line (necessarily disjoint from 0).

Every group  $S_\alpha \in \mathcal{G}_{\text{straight}}^{2,3}$  is of rank 2, admits a left-invariant Riemannian metric of nonpositive curvature, and is irreducible provided its weights are pairwise distinct — see Proposition A.1 in the appendix for a proof of these properties (in wider generality). Therefore, in some sense,  $\mathcal{G}_{\text{straight}}^{2,3}$  appears as the simplest family of irreducible higher-rank nonpositively curved Lie groups.

Our first result exhibits a critical exponent of the  $L^p$ -cohomology, in degree 2, of the groups that belong to  $\mathcal{G}_{\text{straight}}^{2,3}$ . It partially answers a question of Cornulier.

**Theorem A** *Let  $S_\alpha \in \mathcal{G}_{\text{straight}}^{2,3}$ . Its weights  $\varpi_1, \varpi_2, \varpi_3$  belong to a line. Since permuting the coordinates of  $\mathbb{R}^3$  preserves the isomorphism class of  $S_\alpha$ , we can (and will) assume that the algebraic distances between the weights on the (suitably oriented) line satisfy  $0 \leq \varpi_2 - \varpi_3 \leq \varpi_1 - \varpi_2$ . Set*

$$p_\alpha := 1 + \frac{\varpi_1 - \varpi_3}{\varpi_1 - \varpi_2} \in [2; 3].$$

*Then  $L^p H_{\text{dR}}^2(S_\alpha) = \{0\}$  for  $p \in (1; p_\alpha) \setminus \{\frac{3}{2}\}$ , and  $L^p H_{\text{dR}}^2(S_\alpha) \neq \{0\}$  for  $p \in (p_\alpha; +\infty) \setminus \{3\}$ .*

Observe that two triples  $(\varpi_1, \varpi_2, \varpi_3)$  and  $(\varpi'_1, \varpi'_2, \varpi'_3)$  — of distinct elements in  $(\mathbb{R}^2)^*$  that are aligned on lines disjoint from 0 — belong to the same  $\text{GL}_2(\mathbb{R})$ -orbit if, and only, if

$$\frac{\varpi_1 - \varpi_3}{\varpi_1 - \varpi_2} = \frac{\varpi'_1 - \varpi'_3}{\varpi'_1 - \varpi'_2}.$$

Since precomposing  $\alpha$  by an element of  $\mathrm{GL}_2(\mathbb{R})$  preserves the isomorphism class of  $S_\alpha$ , and since de Rham  $L^p$ -cohomology is a quasi-isometry invariant among Lie groups that are diffeomorphic to  $\mathbb{R}^D$  (see Pansu [1995] and Bourdon and Rémy [2023, Appendice]), Theorem A admits the following rigidity consequence:

**Corollary B** *Among the groups in  $\mathcal{G}_{\text{straight}}^{2,3}$ , any two of them are quasi-isometric if, and only if, they are isomorphic.*

Theorem A also yields:

**Corollary C** *There exists a continuum of quasi-isometry classes of rank 2 solvable irreducible nonpositively curved Lie groups.*

**The symmetric space  $\mathrm{SL}_3(\mathbb{R})/\mathrm{SO}_3(\mathbb{R})$**  Going back to semisimple groups, the same approach, which we describe below in more detail, enables us to exhibit another critical exponent in degree 2:

**Theorem D** *Let  $S$  be the symmetric space  $\mathrm{SL}_3(\mathbb{R})/\mathrm{SO}_3(\mathbb{R})$ , or equivalently the Borel subgroup of  $\mathrm{SL}_3(\mathbb{R})$  consisting of upper-triangular matrices with positive diagonal entries. Then  $L^p H_{\mathrm{dR}}^2(S)$  is zero for  $p \in (1; 2) \setminus \{\frac{4}{3}\}$ , and nonzero for  $p \in (2; +\infty) \setminus \{4\}$ .*

By Iwasawa decomposition, the symmetric space  $S$  is naturally isometric to the Borel subgroup of  $\mathrm{SL}_3(\mathbb{R})$ ; the latter is a specific rank 2 solvable group, namely a semidirect product of  $\mathbb{R}^2$  and of the Heisenberg group in dimension 3.

**About the proofs** In both instances of the solvable groups dealt with in the above theorems, we can decompose the action of  $\mathbb{R}^2$  on the 3-dimensional subgroup  $\mathbb{R}^3$  (resp. on the Heisenberg group in dimension 3, which we denote by  $\mathrm{Heis}(3)$ ) into two steps. In a first step, one factor  $\mathbb{R}$  of  $\mathbb{R}^2$  acts on  $\mathbb{R}^3$  (resp. on  $\mathrm{Heis}(3)$ ) so that the intermediate (rank 1) semidirect product is a nonunimodular solvable group isometric to the real (resp. complex) hyperbolic space of real dimension 4. Then, as a second step, we consider the action of the second factor  $\mathbb{R}$  of  $\mathbb{R}^2$  and use a spectral sequence argument, together with the fact that we understand in detail the cohomology of the intermediate 4-dimensional group of the first step. Thus, at this stage, proving the nonvanishing of the considered  $L^p$ -cohomology amounts to showing that some de Rham classes on the rank 1 group satisfy a certain  $L^p$ -integrability condition; see Section 5.3, and relation (7.7) in Section 7.4. The vanishing part requires a Poincaré duality argument to show the requested nonintegrability of the relevant de Rham classes.

The main result about the rank 1 intermediate solvable groups above is Theorem 3.2. It provides a partial description of the  $L^p$ -cohomology of Lie groups containing a suitable 1-parameter subgroup of (semi) contractions acting on its complement. The obtained description complements some previous results of Pansu [1999, Sections 9 and 10]; we call it a *strip decomposition* since its hypotheses are stated as (double) inequalities that must be satisfied by the exponent  $p$  with respect to quantities depending on

the degree  $k$  of the cohomology and on the infinitesimal eigenvalues of the contraction group. The conclusions deal with the following properties: vanishing, Hausdorff property, density of some explicit subspaces of closed forms, and finally Poincaré duality realized at infinity, ie on the group-theoretic complement of the contraction group (which is a Lie group seen as a boundary of the ambient group).

The statement of Theorem 3.2 is applied to the special semidirect products  $\mathbb{R} \ltimes \mathbb{R}^n$  and  $\mathbb{R} \ltimes \text{Heis}(2m - 1)$ , which are isometric to the real hyperbolic space  $\mathbb{H}_{\mathbb{R}}^{n+1}$  and to the complex one  $\mathbb{H}_{\mathbb{C}}^m$ . We obtain in this way a rather precise description of the  $L^p$ -cohomology of  $\mathbb{H}_{\mathbb{R}}^{n+1}$ . In the case of the complex hyperbolic space, the information given by Theorem 3.2 is fragmented, and a substantial additional amount of work dealing with Heisenberg groups of arbitrary dimension, elaborating on ideas due to Rumin [1994] and Pansu [2011], is required.

Again, from a technical point of view, the paper deals with de Rham cohomology only, and some of our results are valid for Riemannian manifolds endowed with a suitable contracting vector field, even though the main applications are relevant to the Lie group situation. This applies in particular to the main new technical result (Theorem 2.5), which translates the Poincaré duality in terms of currents on the “boundary”.

Let us finish this introduction with some remarks.

**Remark 0.1** Pansu [1999, Corollary 2] has already used  $L^p$ -cohomology to show that the groups  $H_{\alpha} := \mathbb{R} \ltimes_{\alpha} \mathbb{R}^n$ , with

$$\alpha(t) = \text{diag}(e^{-\alpha_1 t}, \dots, e^{-\alpha_n t}) \quad \text{and} \quad 1 = \alpha_1 \leq \alpha_2 \leq \dots \leq \alpha_n,$$

form a continuous family of pairwise nonquasi-isometric Heintze groups; see also Sequeira [2024]. This result has been generalized by Xie [2014, Corollary 1.3] to nondiagonal automorphisms, by using more geometric methods.

**Remark 0.2** It is a natural to ask whether the rigidity statement of Corollary B remains true for other families of groups, like the families  $\mathcal{G}^{r,n}$  considered in the appendix. This question has been already studied in some special cases, eg for the family evoked just above in Remark 0.1. Eskin, Fisher and Whyte [Eskin et al. 2012] study the groups  $\text{Sol}_{\lambda} := \mathbb{R} \ltimes_{\lambda} \mathbb{R}^2$ , where  $\lambda \geq 1$ , and where  $\mathbb{R}$  acts on  $\mathbb{R}^2$  via  $t \mapsto e^{tB_{\lambda}}$ , with

$$B_{\lambda} = \begin{pmatrix} 1 & 0 \\ 0 & -\lambda \end{pmatrix}.$$

They show that these groups are pairwise nonquasi-isometric. Observe that the groups  $\text{Sol}_{\lambda}$  are rank 1 solvable Lie groups that do not carry any nonpositively curved left-invariant Riemannian metric; see Proposition A.1(3).

Peng [2011b, Corollary 5.3.7] established that if  $G = \mathbb{R}^r \ltimes_{\varphi} \mathbb{R}^n$  and  $G' = \mathbb{R}^{r'} \ltimes_{\varphi'} \mathbb{R}^{n'}$  are two quasi-isometric, *unimodular*, nondegenerate split abelian-by-abelian solvable Lie groups, then there exists

an isomorphism  $f: \mathbb{R}^r \rightarrow \mathbb{R}'^r$  such that  $\varphi$  and  $\varphi' \circ f$  have the same Jordan form. Again, due to the unimodularity, these groups do not carry any nonpositively curved left-invariant Riemannian metric.

**Remark 0.3** Examples of nonpositively curved, rank 2, *reducible*, solvable Lie groups, include the groups  $\mathbb{R} \times H_\lambda$  (in dimension 4), and the groups  $\mathbb{H}_{\mathbb{R}}^2 \times H_\lambda$  (in dimension 5); where  $H_\lambda$  for  $\lambda \geq 1$  is the Heintze group defined in the overview. As a consequence of a general quasi-isometric rigidity theorem for product metric spaces [Kapovich et al. 1998, Theorem B], all these groups are pairwise nonquasi-isometric.

**Remark 0.4** Our results on de Rham  $L^p$ -cohomology of hyperbolic spaces can be compared with Borel's results [1985] on  $L^2$ -cohomology of symmetric spaces. It turns out that for complex hyperbolic spaces our results are complementary in the sense that the exponent  $p = 2$  is never contained in the interior of the strips we distinguish. Nevertheless, for  $\mathbb{H}_{\mathbb{C}}^m$  it is in the closure (and in the middle) of the union  $(2m/(m+1); 2) \sqcup (2; 2m/(m-1))$  of two critical strips. For  $p$  in the interior of each segment, our Theorem 6.1 says that  $L^p H_{\text{dR}}^m(\mathbb{H}_{\mathbb{C}}^m)$  is Hausdorff and nonzero, while Theorem A of [loc. cit.] asserts that the statement is true for  $p = 2$ . Moreover it describes the latter space in representation-theoretic terms. For real hyperbolic spaces  $\mathbb{H}_{\mathbb{R}}^{n+1}$ , we have to distinguish two cases, according to the parity of  $n$ . When  $n$  is odd, our Theorem 4.1 recovers Theorem A(i) of [loc. cit.], saying that  $L^2 H_{\text{dR}}^\bullet(\mathbb{H}_{\mathbb{R}}^{n+1})$  is Hausdorff and concentrated in degree  $\frac{1}{2}(n+1)$ . When  $n$  is even, Theorem B of [loc. cit.] complements our result, saying that  $L^2 \overline{H}_{\text{dR}}(\mathbb{H}_{\mathbb{R}}^{n+1})$  is zero and  $L^2 H_{\text{dR}}^\bullet(\mathbb{H}_{\mathbb{R}}^{n+1})$  is not Hausdorff in degree  $\frac{1}{2}n+1$ .

**Structure of the paper** Section 1 introduces currents in the context of  $L^p$ -cohomology; it also recalls Poincaré duality for its reduced variant. Section 2 introduces flows with suitable contraction properties on manifolds; it describes their effects on  $L^p$ -cohomology and introduces a version of Poincaré duality involving currents on the “boundary” of such a manifold. In Section 3, the situation is specialized to the case of Lie groups; the existence of a suitable 1-dimensional (semi)contracting group leads to the strip description of the  $L^p$ -cohomology of the groups under consideration. In Section 4, we apply the result of the previous section to deduce the description of the  $L^p$ -cohomology of real hyperbolic spaces. Section 5 focuses on the proof of Theorem A about the second  $L^p$ -cohomology of the groups  $S_\alpha$ ; this is where we determine our first critical exponent. Section 6 provides a description of the  $L^p$ -cohomology of complex hyperbolic spaces; this requires more care than for the real case, and in particular it leads to an intensive use of Heisenberg groups. In Section 7, using the same strategy as in Section 5, we determine our second higher-rank critical exponent, this time for the symmetric space  $\text{SL}_3(\mathbb{R})/\text{SO}_3(\mathbb{R})$ . Lastly, an appendix deals with the groups  $S_\alpha$  in a wider generality, and establishes some of their basic properties.

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# 1 Currents and *L<sup>p</sup>*-cohomology

In this section, we give a quick presentation of de Rham *L<sup>p</sup>*-cohomology and related topics.

## 1.1 Currents

Currents play a central role in classical de Rham cohomology. We recall some of the basic definitions and properties useful for the *L<sup>p</sup>* variant; see [Dinh and Sibony 2005] for more information.

Let *M* be a *C<sup>∞</sup>* orientable *D*-manifold without boundary. For *k* ∈ ℤ, let Ω<sup>*k*</sup>(*M*) be the space of *C<sup>∞</sup>* differential *k*-forms on *M*, and let Ω<sub>*c*</sub><sup>*k*</sup>(*M*) be the space of compactly supported *C<sup>∞</sup>* differential *k*-forms, endowed with the *C<sup>∞</sup>* topology. As usual we set Ω<sup>*k*</sup>(*M*) = Ω<sub>*c*</sub><sup>*k*</sup>(*M*) = {0} for *k* < 0.

A *k*-current on *M* is by definition a continuous real-valued linear form on Ω<sub>*c*</sub><sup>*D-k*</sup>(*M*). We denote by ℳ<sup>*k*</sup>(*M*) the space of *k*-currents on *M* endowed with the weak\*-topology.

To every ω ∈ Ω<sup>*k*</sup>(*M*), one associates the *k*-current *T<sub>ω</sub>* defined by *T<sub>ω</sub>*(α) := ∫<sub>*M*</sub> ω ∧ α. This defines an embedding of Ω<sup>*k*</sup>(*M*) into ℳ<sup>*k*</sup>(*M*), whose image is known to be dense. The differential of a *k*-current *T* is the (*k*+1)-current *dT* defined by *dT*(α) := (-1)<sup>*k*+1</sup> *T*(*dα*) for every α ∈ Ω<sub>*c*</sub><sup>*D-k-1*</sup>(*M*). The map *d* so obtained satisfies *d* ∘ *d* = 0. Since *M* is assumed to have no boundary, this definition is consistent with Stokes' formula

$$\int_M d\omega \wedge \alpha = (-1)^{k+1} \int_M \omega \wedge d\alpha,$$

and gives in particular *dT<sub>ω</sub>* = *T<sub>dω</sub>*.

More generally, suppose we are given ℓ ∈ ℤ, and a continuous linear operator *L*: Ω<sup>\*</sup>(*M*) → Ω<sup>*\*-ℓ*</sup>(*N*), where *M* and *N* are orientable manifolds of dimensions *D<sub>M</sub>* and *D<sub>N</sub>* respectively, such that there is a continuous operator  $\tilde{L}: \Omega_c^{D_N-*+\ell}(N) \rightarrow \Omega_c^{D_M-*}(M)$  with

$$\int_N L(\omega) \wedge \alpha = \int_M \omega \wedge \tilde{L}(\alpha)$$

for every ω ∈ Ω<sup>\*</sup>(*M*) and α ∈ Ω<sub>*c*</sub><sup>*D<sub>N</sub>-\*+ℓ*</sup>(*N*). Then *L* extends by continuity to ℳ<sup>*\**</sup>(*M*) → ℳ<sup>*\*-ℓ*</sup>(*N*) by setting (*L*(*T*))(α) := *T*( $\tilde{L}(\alpha)$ ). This applies for instance to inner products  $\iota_\xi: \Omega^*(M) \rightarrow \Omega^{*-1}(M)$  by a vector field ξ on *M*. One has  $\tilde{\iota}_\xi = (-1)^{k+1} \iota_\xi$  on Ω<sub>*c*</sub><sup>*D-k+1*</sup>(*M*), since  $\iota_\xi$  is an antiderivation; see eg [Tu 2008, Proposition 20.8].

In local coordinates (x<sub>1</sub>, . . . , x<sub>*D*</sub>) on an open subset *U* ⊂ *M*, every *k*-current *T* ∈ ℳ<sup>*k*</sup>(*U*) can be written *T* = ∑<sub>|*I*|=*k*</sub> *T<sub>I</sub>* dx<sub>*I*</sub>, with *T<sub>I</sub>* ∈ ℳ<sup>0</sup>(*U*). For every α ∈ Ω<sub>*c*</sub><sup>*D-k*</sup>(*U*), one has *T*(α) = ∑<sub>|*I*|=*k*</sub> *T<sub>I</sub>*(dx<sub>*I*</sub> ∧ α).

## 1.2 De Rham *L<sup>p</sup>*-cohomology: definitions and notation

We list and fix the definitions and notation for several objects that will appear repeatedly in the paper.

Let *M* be a *C<sup>∞</sup>* orientable manifold (without boundary), henceforth endowed with a Riemannian metric. We denote by *dvol* its Riemannian measure, and by |*v*| the Riemannian length of a vector *v* ∈ *TM*.

- Let  $p \in (1, +\infty)$ . The  $L^p$ -norm of  $\omega \in \Omega^k(M)$  is

$$\|\omega\|_{L^p\Omega^k} = \left( \int_M |\omega|_m^p d\text{vol}(m) \right)^{1/p},$$

where we set

$$|\omega|_m := \sup\{|\omega(m; v_1, \dots, v_k)| : v_1, \dots, v_k \in T_m M, |v_i| = 1\}.$$

- The space  $L^p\Omega^k(M)$  is the norm completion of the normed space  $\{\omega \in \Omega^k(M) : \|\omega\|_{L^p\Omega^k} < +\infty\}$ , ie the Banach space of  $k$ -differential forms with measurable  $L^p$  coefficients.
- To every  $\omega \in L^p\Omega^k(M)$ , one associates the  $k$ -current  $T_\omega$  defined by  $T_\omega(\alpha) := \int_M \omega \wedge \alpha$ . The differential in the sense of currents of  $\omega \in L^p\Omega^k(M)$  is the  $(k+1)$ -current  $d\omega := dT_\omega$ . One says that  $d\omega$  belongs to  $L^p\Omega^{k+1}(M)$  if there exists  $\theta \in L^p\Omega^{k+1}(M)$  such that  $d\omega = T_\theta$ . In this case we set  $\|d\omega\|_{L^p\Omega^{k+1}} := \|\theta\|_{L^p\Omega^{k+1}}$ .
- For  $\omega \in \Omega^k(M)$ , we set

$$\|\omega\|_{\Omega^{p,k}} := \|\omega\|_{L^p\Omega^k} + \|d\omega\|_{L^p\Omega^{k+1}}.$$

The space  $\Omega^{p,k}(M)$  is the norm completion of the normed space  $\{\omega \in \Omega^k(M) : \|\omega\|_{\Omega^{p,k}} < +\infty\}$ . It is a Banach space that coincides with the subspace of  $L^p\Omega^k(M)$  consisting of the  $L^p$   $k$ -forms whose differentials in the sense of currents belong to  $L^p\Omega^{k+1}(M)$ . Moreover, the differential operator  $d$  on  $\Omega^{p,*}(M)$  agrees with the differential in the sense of currents; see eg [Bourdon and Rémy 2023, Lemma 1.5] for a proof.

- The de Rham  $L^p$ -cohomology of  $M$  is the cohomology of the complex

$$\Omega^{p,0}(M) \xrightarrow{d_0} \Omega^{p,1}(M) \xrightarrow{d_1} \Omega^{p,2}(M) \xrightarrow{d_2} \dots$$

It is denoted by  $L^pH_{\text{dR}}^*(M)$ . Its largest Hausdorff quotient is denoted by  $L^p\overline{H}_{\text{dR}}^*(M)$  and is called the reduced de Rham  $L^p$ -cohomology of  $M$ . The latter is a Banach space; its (quotient) norm is denoted by  $\|\cdot\|_{L^p\overline{H}^*}$ .

- Following Pansu, we also define  $\Psi^{p,k}(M)$  to be the space of  $k$ -currents  $\psi \in \mathcal{D}^k(M)$  that can be written as  $\psi = \beta + d\gamma$ , with  $\beta \in L^p\Omega^k(M)$  and  $\gamma \in L^p\Omega^{k-1}(M)$ . In particular, we have  $\Psi^{p,0}(M) = L^p(M)$ . Equipped with the norm

$$\|\psi\|_{\Psi^{p,k}} := \inf\{\|\beta\|_{L^p\Omega^k} + \|\gamma\|_{L^p\Omega^{k-1}} : \psi = \beta + d\gamma, \text{ with } \beta \in L^p\Omega^k(M) \text{ and } \gamma \in L^p\Omega^{k-1}(M)\},$$

the space  $\Psi^{p,k}(M)$  is a Banach space, and the inclusion maps between differential complexes

$$\Omega^{p,*}(M) \subset \Psi^{p,*}(M) \subset \mathcal{D}^*(M)$$

are continuous; see [Bourdon and Rémy 2023, Lemma 1.7] for a proof.

- Suppose that  $M$  carries a  $C^\infty$  unit complete vector field  $\xi$ , and let  $(\varphi_t)_{t \in \mathbb{R}}$  be its flow. Assume that  $\varphi_t^*: L^p \Omega^k(M) \rightarrow L^p \Omega^k(M)$  is bounded for all  $t \in \mathbb{R}$ ,  $p \in (1, +\infty)$  and  $k \in \mathbb{N}$ . We set

$$\Psi^{p,k}(M, \xi) := \{\psi \in \Psi^{p,k}(M) : \varphi_t^*(\psi) = \psi \text{ for every } t \in \mathbb{R}\}.$$

The differential complex  $\Psi^{p,*}(M, \xi)$  is a closed subcomplex of  $\Psi^{p,*}(M)$ . Let

$$\mathcal{Z}^{p,k}(M, \xi) := \text{Ker}(d: \Psi^{p,k}(M, \xi) \rightarrow \Psi^{p,k+1}(M, \xi))$$

be the space of  $k$ -cocycles.

### 1.3 Poincaré duality

Poincaré duality for de Rham  $L^p$ -cohomology takes the following form.

**Proposition 1.1** *Let  $M$  be a complete oriented Riemannian manifold of dimension  $D$ . Let  $p \in (1, +\infty)$ ,  $q = p/(p - 1)$  be its Hölder conjugate, and  $k \in \{0, \dots, D\}$ . Then:*

- (1)  $L^p H_{\text{dR}}^k(M)$  is Hausdorff if and only if  $L^q H_{\text{dR}}^{D-k+1}(M)$  is.
- (2)  $L^p \overline{H}_{\text{dR}}^k(M)$  and  $L^q \overline{H}_{\text{dR}}^{D-k}(M)$  are dual Banach spaces, via the perfect pairing

$$L^p \overline{H}_{\text{dR}}^k(M) \times L^q \overline{H}_{\text{dR}}^{D-k}(M) \rightarrow \mathbb{R}, \quad ([\omega_1], [\omega_2]) \mapsto \int_M \omega_1 \wedge \omega_2.$$

**Proof** See [Pansu 2008, Corollaire 14] or [Gol'dshtein and Troyanov 2010]. □

The following terminology will be useful in the sequel.

**Definition 1.2** Let  $p, q \in (1, +\infty)$  and  $k, \ell \in \{0, \dots, D\}$ . The couples  $(p, k)$  and  $(q, \ell)$  are said to be *Poincaré dual* if  $p$  and  $q$  are Hölder conjugate and if  $\ell = D - k$ .

## 2 Flows and $L^p$ -cohomology

This section exploits some dynamical properties of flows acting on forms to extract information on  $L^p$ -cohomology. The objects appearing in this section are defined in Section 1.2. In what follows, we keep  $M$  a  $C^\infty$  orientable manifold (without boundary) endowed with a Riemannian metric.

### 2.1 Invariance, identification and vanishing

We review several results due to Pansu [2008, Proposition 10]; see also Bourdon and Rémy [2023, Section 1].

Let  $\xi$  be a  $C^\infty$  unit complete vector field on  $M$ , and denote by  $(\varphi_t)_{t \in \mathbb{R}}$  its flow. We assume that  $\varphi_t^*: L^p \Omega^k(M) \rightarrow L^p \Omega^k(M)$  is bounded for all  $t \in \mathbb{R}$ ,  $p \in (1, +\infty)$  and  $k \in \mathbb{N}$ . This happens for instance when  $M$  is a manifold of *bounded geometry*, ie a manifold whose injectivity radius is bounded from below and whose sectional curvatures are bounded from above and from below.

**Proposition 2.1** *Let  $p \in (1, +\infty)$  and let  $k \in \mathbb{N}$ . Then for every  $\omega \in \Omega^{p,k}(M) \cap \text{Ker } d$  and  $t \in \mathbb{R}$ , the forms  $\omega$  and  $\varphi_t^* \omega$  are cohomologous in  $L^p H_{\text{dR}}^k(M)$ .*

**Proof** See for example [Bourdon and Rémy 2023, Lemma 1.3]. □

**Proposition 2.2** *Let  $p \in (1, +\infty)$  and  $k \in \mathbb{N}^*$ . Suppose that there exist  $C, \eta > 0$  such that for every  $t \geq 0$ , one has*

$$\|\varphi_t^*\|_{L^p \Omega^{k-1} \rightarrow L^p \Omega^{k-1}} \leq C e^{-\eta t}.$$

Then:

- (1) *Let  $\omega \in \Omega^{p,k}(M) \cap \text{Ker } d$ . When  $t \rightarrow +\infty$ , the form  $\varphi_t^* \omega$  converges in the Banach space  $\Psi^{p,k}(M)$  (and so in the sense of currents); its limit  $\omega_\infty$  is a closed current in  $\mathcal{X}^{p,k}(M, \xi)$ .*
- (2) *The map  $\omega \mapsto \omega_\infty$  induces a canonical Banach isomorphism*

$$L^p H_{\text{dR}}^k(M) \simeq \mathcal{X}^{p,k}(M, \xi).$$

*In particular,  $L^p H_{\text{dR}}^k(M)$  is Hausdorff.*

**Proof** The statement is essentially contained in [Pansu 2008, Proposition 10]. A proof also appears in [Bourdon and Rémy 2023, Proposition 1.9] under the stronger assumption that

$$\max_{i=k-2, k-1} \|\varphi_t^*\|_{L^p \Omega^i \rightarrow L^p \Omega^i} \leq C e^{-\eta t}.$$

The extra assumption served only to prove its parts (3) and (4), showing that  $\lim_{t \rightarrow +\infty} \|\varphi_t^*(d\theta)\|_{\Psi^{p,k}} = 0$  for every  $\theta \in L^p \Omega^{k-1}(M)$ . But the weaker hypothesis  $\|\varphi_t^*\|_{L^p \Omega^{k-1} \rightarrow L^p \Omega^{k-1}} \leq C e^{-\eta t}$  is enough to prove this property. Indeed, by combining the definition of  $\|\cdot\|_{\Psi^{p,k}}$  with this assumption, one has

$$\|\varphi_t^*(d\theta)\|_{\Psi^{p,k}} = \|d(\varphi_t^* \theta)\|_{\Psi^{p,k}} \leq \|\varphi_t^* \theta\|_{L^p \Omega^{k-1}} \rightarrow 0 \quad \text{when } t \rightarrow \infty. \quad \square$$

**Corollary 2.3** *Let  $p \in (1, +\infty)$  and  $k \in \mathbb{N}^*$ . Suppose that there exist  $C, \eta > 0$  such that for every  $t \geq 0$ , one has*

$$\max_{i=k-1, k} \|\varphi_t^*\|_{L^p \Omega^i \rightarrow L^p \Omega^i} \leq C e^{-\eta t}.$$

Then  $L^p H_{\text{dR}}^k(M) = \{0\}$ .

**Proof** Our assumption implies that  $\|\varphi_t^*\|_{\Psi^{p,k} \rightarrow \Psi^{p,k}} \leq C e^{-\eta t}$ ; and also that  $L^p H_{\text{dR}}^k(M) \simeq \mathcal{X}^{p,k}(M, \xi)$  by Proposition 2.2. Since the elements of  $\mathcal{X}^{p,k}(M, \xi)$  are  $\varphi_t$ -invariant, one gets that  $\mathcal{X}^{p,k}(M, \xi) = \{0\}$ . Therefore  $L^p H_{\text{dR}}^k(M) = \{0\}$ . □

### 2.2 Boundary values, Poincaré duality revisited

In this section, the oriented Riemannian manifold  $M$  is supposed to be complete. We assume furthermore that  $M$  and the unit vector field  $\xi$  are such that the pair  $(M, \xi)$  is  $C^\infty$ -diffeomorphic to a pair of the form  $(\mathbb{R} \times N, \partial/\partial t)$ , where the vector field  $\partial/\partial t$  is carried by the  $\mathbb{R}$ -factor.

We think of  $N$  as a “boundary” of  $M$ . Under some dynamical assumptions, we will represent the spaces  $L^p H_{\mathbb{R}}^k(M)$  and the Poincaré duality on the boundary  $N$ ; see Proposition 2.4 and Theorem 2.5 below.

Let  $\pi : M \rightarrow N$  be the projection map and  $\pi^* : \mathcal{D}^i(N) \rightarrow \mathcal{D}^i(M)$  be the continuous extension of the pullback map  $\pi^* : \Omega^i(N) \rightarrow \Omega^i(M)$ . We set  $n =: \dim N$  so that  $D := \dim M = n + 1$ .

**Proposition 2.4** *Let  $p \in (1, +\infty)$  and  $k \in \mathbb{N}^*$ . Suppose that there exist  $C, \eta > 0$  such that for  $t \geq 0$ ,*

$$\|\varphi_t^*\|_{L^p \Omega^{k-1} \rightarrow L^p \Omega^{k-1}} \leq C e^{-\eta t}.$$

*Then for every  $\psi \in \mathcal{X}^{p,k}(M, \xi)$ , there exists  $T \in \mathcal{D}^k(N) \cap \text{Ker } d$  such that  $\psi = \pi^*(T)$ .*

**Proof** Recall that  $\xi = \partial/\partial t$  and that the flow of  $\xi$  is denoted by  $\varphi_t$ . Every  $\psi \in \mathcal{X}^{p,k}(M, \xi)$  is  $\varphi_t$ -invariant; thus it can be decomposed as  $\psi = \pi^*(S) \wedge dt + \pi^*(T)$ , where  $S \in \mathcal{D}^{k-1}(N)$  and  $T \in \mathcal{D}^k(N)$ . Therefore, showing that  $\psi = \pi^*(T)$  is equivalent to proving that  $\iota_\xi \psi = 0$ . From Proposition 2.2, there exists  $\omega \in \Omega^{p,k}(M) \cap \text{Ker } d$  such that  $\psi = \lim_{t \rightarrow +\infty} \varphi_t^*(\omega)$  in the sense of currents. Since the map  $\iota_\xi : \mathcal{D}^k(M) \rightarrow \mathcal{D}^{k-1}(M)$  is continuous, one obtains that  $\iota_\xi \psi = \lim_{t \rightarrow +\infty} \varphi_t^*(\iota_\xi \omega)$  in the sense of currents. But  $\iota_\xi \omega \in L^p \Omega^{k-1}(M)$ , and by assumption one has  $\|\varphi_t^*\|_{L^p \Omega^{k-1} \rightarrow L^p \Omega^{k-1}} \rightarrow 0$  when  $t \rightarrow +\infty$ . Thus  $\iota_\xi \psi = 0$ .

Lastly, since  $d\psi = 0$ , one gets that  $\pi^*(dT) = 0$ , which in turn implies that  $dT = 0$ . Thus, as expected,  $T \in \mathcal{D}^k(N) \cap \text{Ker } d$ . □

Let  $\chi$  be a nonnegative  $C^\infty$  function on  $M$ , depending only on the  $\mathbb{R}$ -variable, such that  $\chi(t) = 0$  for  $t \leq 0$  and  $\chi(t) = 1$  for  $t \geq 1$ .

**Theorem 2.5** *Let  $p, q \in (1, +\infty)$  and  $k, \ell \in \{1, \dots, n\}$  be such that  $(p, k)$  and  $(q, \ell)$  are Poincaré dual; see Definition 1.2. Suppose that there exist  $C, \eta > 0$  such that for  $t \geq 0$ ,*

- (1)  $\|\varphi_t^*\|_{L^p \Omega^{k-1} \rightarrow L^p \Omega^{k-1}} \leq C e^{-\eta t}$ ,
- (2)  $\|\varphi_{-t}^*\|_{\text{Ker } \iota_\xi \cap L^q \Omega^\ell \rightarrow \text{Ker } \iota_\xi \cap L^q \Omega^\ell} \leq C e^{-\eta t}$ .

*Then for every  $\theta \in \Omega_c^{\ell-1}(N)$ , the form  $d(\chi \cdot \pi^* \theta)$  belongs to the space  $\Omega^{q,\ell}(M) \cap \text{Ker } d$ ; and for every  $\omega \in \Omega^{p,k}(M) \cap \text{Ker } d$ , one has*

$$\int_M \omega \wedge d(\chi \cdot \pi^* \theta) = T(\theta),$$

*where  $T$  is the closed  $k$ -current on  $N$  such that*

$$\omega_\infty = \lim_{t \rightarrow +\infty} \varphi_t^*(\omega) = \pi^*(T),$$

*as in Propositions 2.2 and 2.4.*

As a consequence of Theorem 2.5, we will prove:

**Corollary 2.6** *Suppose that the assumptions of Theorem 2.5 are satisfied. Then the classes of the forms  $d(\chi \cdot \pi^* \theta)$ , where  $\theta \in \Omega_c^{\ell-1}(N)$ , form a dense subspace in  $L^q \overline{H}_{dR}^\ell(M)$ . Moreover, when  $\theta = d\alpha$  is an exact form, with  $\alpha \in \Omega_c^{\ell-2}(N)$ , then  $[d(\chi \cdot \pi^* \theta)] = 0$  in  $L^q \overline{H}_{dR}^\ell(M)$ .*

Recall that  $L^p \overline{H}_{dR}^k(M)$  and  $L^q \overline{H}_{dR}^\ell(M)$  are dual Banach spaces, via the pairing  $([\omega_1], [\omega_2]) \mapsto \int_M \omega_1 \wedge \omega_2$ ; see Proposition 1.1. In combination with Theorem 2.5 and Corollary 2.6 above, this immediately yields:

**Corollary 2.7** *Suppose that the assumptions of Theorem 2.5 are satisfied. Let  $\omega \in \Omega^{p,k}(M) \cap \text{Ker } d$  and let  $T \in \mathcal{D}'^k(N) \cap \text{Ker } d$  be such that  $\lim_{t \rightarrow +\infty} \varphi_t^*(\omega) = \pi^*(T)$ . Then the norm of  $[\omega]$  in  $L^p \overline{H}_{dR}^k(M)$  satisfies*

$$\|[\omega]\|_{L^p \overline{H}^k} = \sup\{T(\theta) : \theta \in \Omega_c^{\ell-1}(N), \| [d(\chi \cdot \pi^* \theta)] \|_{L^q \overline{H}^\ell} \leq 1\}.$$

**Proof of Theorem 2.5 Step 1** We first show that the  $L^q$ -norm of the form  $d(\chi \cdot \pi^* \theta)$  is finite. Set  $\alpha := \pi^* \theta$  for simplicity. One has

$$d(\chi \cdot \alpha) = d\chi \wedge \alpha + \chi \cdot d\alpha.$$

The form  $d\alpha$  belongs to  $\text{Ker } \iota_\xi$  and is  $\varphi_t$ -invariant. With the assumption (2) we obtain (since  $s \geq 0$ ):

$$\begin{aligned} \|\chi \cdot d\alpha\|_{L^q \Omega^\ell} &\leq \|\mathbf{1}_{t \geq 0} \cdot d\alpha\|_{L^q \Omega^\ell} = \sum_{i=0}^{\infty} \|\mathbf{1}_{t \in [i, i+1]} \cdot d\alpha\|_{L^q \Omega^\ell} \\ &\leq C \sum_{i=0}^{\infty} e^{-\eta i} \|\mathbf{1}_{t \in [0, 1]} \cdot d\alpha\|_{L^q \Omega^\ell} = \frac{C}{1 - e^{-\eta}} \|\mathbf{1}_{t \in [0, 1]} \cdot d\alpha\|_{L^q \Omega^\ell}, \end{aligned}$$

which is finite since  $\mathbf{1}_{t \in [0, 1]} \cdot d\alpha$  has compact support.

It remains to bound the  $L^q$ -norm of  $d\chi \wedge \alpha$  from above. One has  $d\chi = \chi'(t) dt$ , with  $\chi'$  supported on  $[0, 1]$ . Thus

$$\|d\chi \wedge \alpha\|_{L^q \Omega^\ell} \leq \|\chi' \cdot \alpha\|_{L^q \Omega^{\ell-1}} \leq C_1 \|\mathbf{1}_{t \in [0, 1]} \cdot \alpha\|_{L^q \Omega^{\ell-1}},$$

with  $C_1 = \|\chi'\|_\infty$ . Since  $\mathbf{1}_{t \in [0, 1]} \cdot \alpha$  has compact support, the  $L^q$ -norm of  $d\chi \wedge \alpha$  is finite too. The statement follows.

**Step 2** We now compute  $\int \omega \wedge d(\chi \cdot \alpha)$ . Since  $\varphi_t^*(\omega)$  and  $\omega$  are cohomologous (by Proposition 2.1), one has, thanks to Proposition 1.1(2),

$$\int \omega \wedge d(\chi \cdot \alpha) = \int \varphi_t^*(\omega) \wedge d(\chi \cdot \alpha) = \int \varphi_t^*(\omega) \wedge d\chi \wedge \alpha + \int \varphi_t^*(\omega) \wedge (\chi \cdot d\alpha).$$

Since the form  $d\chi \wedge \alpha$  belongs to  $\Omega_c^\ell(M)$ , one has

$$\lim_{t \rightarrow \infty} \int \varphi_t^*(\omega) \wedge d\chi \wedge \alpha = (\pi^* T)(d\chi \wedge \alpha).$$

Indeed,  $\varphi_t^*(\omega)$  tends to  $\pi^* T$  in the sense of currents thanks to assumption (1), Propositions 2.2 and 2.4.

One observes that the map  $\pi^*: \mathcal{D}^i(N) \rightarrow \mathcal{D}^i(M)$  can be written as  $(\pi^*T)(\beta) = T(j(\beta))$ , where  $j: \Omega_c^{D-i}(M) \rightarrow \Omega_c^{D-1-i}(N)$  is defined by

$$j(\beta) = \int_{\mathbb{R}} (\iota_\xi \beta)_{(t, \cdot)} dt$$

(recall that  $\xi = \partial/\partial t$ ). Since the inner product is an antiderivation (see eg [Tu 2008, Proposition 20.8]) and since  $\iota_\xi \alpha = 0$ , one has

$$\iota_\xi(d\chi \wedge \alpha) = (\iota_\xi d\chi) \wedge \alpha - d\chi \wedge (\iota_\xi \alpha) = \chi' \cdot \pi^* \theta.$$

Therefore  $j(d\chi \wedge \alpha) = \int_{\mathbb{R}} \chi'(t) \cdot \theta dt = \theta$ , and we obtain

$$(\pi^*T)(d\chi \wedge \alpha) = T(\theta).$$

**Step 3** According to the previous paragraph, it remains to prove that

$$\lim_{t \rightarrow +\infty} \int \varphi_t^*(\omega) \wedge (\chi \cdot d\alpha) = 0.$$

For  $s > 0$ , let  $\chi_s: M \rightarrow \mathbb{R}$  be a  $C^\infty$ -function, depending only on the  $\mathbb{R}$ -variable, such that  $\chi_s(t) = \chi(t)$  for  $t \leq s$  and  $\chi_s(t) = 0$  for  $t \geq s + 1$ . Observe that  $\chi_s \cdot d\alpha$  is  $C^\infty$  with compact support. We claim that

- for every  $s > 0$ , one has  $\lim_{t \rightarrow +\infty} \int \varphi_t^*(\omega) \wedge (\chi_s \cdot d\alpha) = 0$ ,
- $\int \varphi_t^*(\omega) \wedge ((\chi - \chi_s) \cdot d\alpha)$  tends to 0 uniformly in  $t > 0$  when  $s \rightarrow +\infty$ .

As explained above, the claim completes the proof of the theorem. The first item of the claim follows from the same type of argument that we used in Step 2. Note that here we have  $\iota_\xi(\chi_s \cdot d\alpha) = \chi_s \cdot \iota_\xi d(\pi^* \theta) = \chi_s \cdot \iota_\xi \pi^* d\theta = 0$ , since  $\iota_\xi \circ \pi^* = 0$ .

To prove the second item, recall from Proposition 2.2 that  $\varphi_t^*(\omega)$  converges in  $\Psi^{p,k}(M)$  when  $t \rightarrow +\infty$ . Therefore there exists  $M > 0$  such that  $\|\varphi_t^*(\omega)\|_{\Psi^{p,k}} \leq M$  for every  $t > 0$ . Write  $\varphi_t^*(\omega) = \beta_t + d\gamma_t$  with  $\|\beta_t\|_{L^p \Omega^k} + \|\gamma_t\|_{L^p \Omega^{k-1}} \leq 2M$ . Observe that  $(\chi - \chi_s) \cdot d\alpha$  belongs to  $\Omega^{q,\ell}(M)$ . Since  $M$  is complete, the space  $\Omega_c^\ell(M)$  is dense in  $\Omega^{q,\ell}(M)$ ; see [Gol'dshtein and Troyanov 2010, Proof of Lemma 4]. Thus for every  $t > 0$ , one gets with Hölder:

$$\begin{aligned} \left| \int \varphi_t^*(\omega) \wedge ((\chi - \chi_s) \cdot d\alpha) \right| &= \left| \int \beta_t \wedge ((\chi - \chi_s) \cdot d\alpha) + (-1)^k \int \gamma_t \wedge d(\chi - \chi_s) \wedge d\alpha \right| \\ &\leq 2M \|(\chi - \chi_s) \cdot d\alpha\|_{L^q \Omega^\ell} + 2M \|d(\chi - \chi_s) \wedge d\alpha\|_{L^q \Omega^{\ell+1}}. \end{aligned}$$

By the same type of argument that we used in Step 1, one obtains that the last two norms tend to 0 when  $s \rightarrow +\infty$ . □

**Proof of Corollary 2.6** Let  $\omega \in \Omega^{p,k}(M) \cap \text{Ker } d$  be such that

$$\int_M \omega \wedge d(\chi \cdot \pi^* \theta) = 0 \quad \text{for every } \theta \in \Omega_c^{\ell-1}(N).$$

According to Poincaré duality (Proposition 1.1), it is enough to show that  $[w] = 0$  in  $L^p H_{\text{dR}}^k(M)$ . By Propositions 2.2 and 2.4, this is equivalent to  $T = 0$ , where  $T \in D'^k(N) \cap \text{Ker } d$  is the  $k$ -current such that  $\omega_\infty = \pi^*(T)$ . From Theorem 2.5 and our assumption, one has, for every  $\theta \in \Omega_c^{\ell-1}(N)$ ,

$$T(\theta) = \int_M \omega \wedge d(\chi \cdot \pi^* \theta) = 0.$$

Thus  $T = 0$ .

Suppose now that  $\theta = d\alpha$  is an exact form, with  $\alpha \in \Omega_c^{\ell-2}(N)$ . Then by again using Poincaré duality as above, we obtain that the class of  $d(\chi \cdot \pi^* \theta)$  is null in  $L^q \overline{H}_{\text{dR}}^\ell(M)$ , since  $T(\theta) = dT(\alpha) = 0$  for every  $T \in D'^k(N) \cap \text{Ker } d$ . □

### 3 The Lie group case

We consider in this section a connected Lie group  $G = \mathbb{R} \rtimes_\delta H$  whose law is  $(t, x) \cdot (s, y) = (t + s, xe^{t\delta}(y))$ , where  $\delta \in \text{Der}(\mathfrak{h})$  is a derivation of the Lie algebra  $\mathfrak{h}$  of the closed subgroup  $H$ . We will always assume that the eigenvalues of  $\delta$  all have nonpositive real parts, and that  $\text{trace}(\delta) < 0$ . In particular,  $G$  is nonunimodular. We set  $n := \dim H$  so that  $D := \dim G = n + 1$ . Equip  $G$  with a left-invariant Riemannian metric and with the associated Riemannian measure  $d\text{vol}$ .

#### 3.1 A strip decomposition

We exhibit some regions of the set of parameters  $(p, k) \in (1, +\infty) \times \{1, \dots, n\}$ , where the results of the previous sections apply and give some information on the spaces  $L^p H_{\text{dR}}^k(G)$ ; see Theorem 3.2 below. These regions form a kind of a “strip decomposition” of the set of parameters. Examples will be given in Sections 4 and 6.

We start with the following lemma, which translates the norm assumptions that appeared repeatedly in the previous sections into simple inequalities between the exponent  $p$  and the eigenvalues of  $-\delta$ .

Let  $0 \leq \lambda_1 \leq \lambda_2 \leq \dots \leq \lambda_n$  be the ordered list of the real parts of the eigenvalues of  $-\delta$ , enumerated with their multiplicities in the generalized eigenspaces. We denote by  $w_k = \sum_{i=1}^k \lambda_i$  the sum of the  $k$  first real part eigenvalues, and by  $W_k = \sum_{j=0}^{k-1} \lambda_{n-j}$  the sum of the  $k$  last ones. We also set  $w_0 = W_0 = 0$ .

Note that we always have  $w_{k-1} \leq w_k \leq W_k$  and  $w_{k-1} \leq W_{k-1} \leq W_k$ , but the comparison between  $w_k$  and  $W_{k-1}$  is not automatic. This can be seen for instance by considering the example where  $\lambda_1 = \lambda_2 = \dots = \lambda_{n-1} = 1$  and  $\lambda_n = a \geq 1$ ; then for  $a > 2$  we have  $W_{k-1} > w_k$ , for  $a = 2$  we have  $W_{k-1} = w_k$  and for  $a < 2$  we have  $W_{k-1} < w_k$ .

Let  $h = \sum_{i=1}^n \lambda_i > 0$  be the trace of  $-\delta$ . If  $w_k = 0$  (resp.  $W_k = 0$ ), put  $h/w_k := +\infty$  (resp.  $h/W_k := +\infty$ ). One has  $w_k + W_{n-k} = h$  for every  $k \in \{0, \dots, n\}$ ; therefore  $h/w_k$  and  $h/W_{n-k}$  are Hölder conjugated (even if  $w_k$  or  $W_{n-k}$  is 0).

**Lemma 3.1** Let  $\xi = \partial/\partial t$  be the left-invariant vector field on  $G$  carried by the  $\mathbb{R}$ -factor, and let  $\varphi_t$  be its flow (it is just a translation along the  $\mathbb{R}$ -factor). Let  $p, q \in (1, +\infty)$  and  $k, \ell \in \{1, \dots, n\}$  be such that  $(p, k)$  and  $(q, \ell)$  are Poincaré dual. The following properties are equivalent:

(1) There exist  $C, \eta > 0$  such that for  $t \geq 0$ ,

$$\|\varphi_t^*\|_{L^p \Omega^{k-1} \rightarrow L^p \Omega^{k-1}} \leq C e^{-\eta t}.$$

(2) There exist  $C, \eta > 0$  such that for  $t \geq 0$ ,

$$\|\varphi_{-t}^*\|_{\text{Ker } \iota_\xi \cap L^q \Omega^\ell \rightarrow L^q \Omega^\ell \cap \text{Ker } \iota_\xi} \leq C e^{-\eta t}.$$

(3)  $p < h/W_{k-1}$ .

(4)  $q > h/w_\ell$ .

In particular, conditions (1) and (2) in Theorem 2.5 are equivalent when  $M = G$ .

**Proof** The equivalences (1)  $\iff$  (3) and (2)  $\iff$  (4) follow from the same line of arguments as in [Bourdon and Rémy 2023, Proof of Proposition 2.1], see in particular the equalities on lines 9 and 28 in [loc. cit., page 787]. To obtain (3)  $\iff$  (4) one notices that  $h/W_{k-1}$  and  $h/w_\ell$  are Hölder conjugated, since  $w_{D-k} + W_{k-1} = h$ .  $\square$

We can now summarize and specify the results of the previous sections, to obtain the following statement that complements results of Pansu [1999, Corollaire 53 and Proposition 57].

**Theorem 3.2** Let  $G$  be a Lie group as above. Let  $p \in (1, +\infty)$  and  $k \in \{1, \dots, n\}$ .

(1) **Vanishing** If  $p < h/W_k$  or  $p > h/w_{k-1}$ , then  $L^p H_{\text{dR}}^k(G) = \{0\}$ .

(2) **Hausdorff property** If  $h/W_k < p < h/W_{k-1}$ , then  $L^p H_{\text{dR}}^k(G)$  is Hausdorff and Banach-isomorphic to  $\mathfrak{X}^{p,k}(G, \xi)$ .

(3) **Density** If  $h/w_k < p < h/w_{k-1}$ , then the classes of the forms  $d(\chi \cdot \pi^* \theta)$ , where  $\theta \in \Omega_c^{k-1}(H)$ , form a dense subspace in  $L^p \overline{H}_{\text{dR}}^k(G)$ .

(4) **Poincaré duality (on the boundary)** Let  $(q, \ell)$  be the Poincaré dual of  $(p, k)$ . Then we have  $h/W_k < p < h/W_{k-1}$  if and only if  $h/w_\ell < q < h/w_{\ell-1}$ , in which case for every  $[\omega] \in L^p \overline{H}_{\text{dR}}^k(G)$  and every  $[d(\chi \cdot \pi^* \theta)] \in L^q \overline{H}_{\text{dR}}^\ell(G)$ , we have

$$\int_G \omega \wedge d(\chi \cdot \pi^* \theta) = T(\theta),$$

where  $T$  is the closed  $k$ -current on  $H$  such that  $\lim_{t \rightarrow +\infty} \varphi_t^*(\omega) = \pi^*(T)$  (as in Propositions 2.2 and 2.4). Moreover, one has

$$\|[\omega]\|_{L^p H^k} = \sup\{T(\theta) : \theta \in \Omega_c^{\ell-1}(H), \| [d(\chi \cdot \pi^* \theta)] \|_{L^q \overline{H}^\ell} \leq 1\}.$$

**Proof** Item (2) follows from Proposition 2.2 and Lemma 3.1. Item (3) is a consequence of Corollary 2.6 and Lemma 3.1. One deduces item (4) from Theorem 2.5, Corollary 2.7 and Lemma 3.1.

It remains to prove item (1). Suppose first that  $p < h/W_k$ . Since  $h/W_k \leq h/W_{k-1}$ , Lemma 3.1 implies that  $\max_{i=k-1,k} \|\varphi_i^*\|_{L^p\Omega^i \rightarrow L^p\Omega^i} \leq Ce^{-\eta t}$ . Thus by Corollary 2.3, one has  $L^pH_{\text{dR}}^k(G) = \{0\}$ , and the first part of item (1) is proved. The second part follows from the first one, in combination with Poincaré duality (Proposition 1.1), and the fact that  $L^qH_{\text{dR}}^{D-k+1}(G)$  is Hausdorff follows from Lemma 3.1 and Proposition 2.2. □

**Remark 3.3** In the special case where  $H = \mathbb{R}^n$ , Pansu [2008, Proposition 27] has filled in the picture seen in Theorem 3.2 by showing that the *torsion* in  $L^pH_{\text{dR}}^k(G)$  —ie the kernel of the quotient map  $L^pH_{\text{dR}}^k(G) \rightarrow L^p\overline{H}_{\text{dR}}^k(G)$  — is nonzero for  $h/W_{k-1} < p < h/w_{k-1}$  (note that there is no such  $p$  for real hyperbolic spaces).

### 3.2 Norm estimates

We now turn to the norm expression obtained in Theorem 3.2(4). The following inequalities are not optimal, however they are often sufficient for our purposes.

**Proposition 3.4** *Let  $\ell \in \{1, \dots, n\}$  and  $q > h/w_\ell$ . There exists a constant  $C > 0$  such that for every  $\theta \in \Omega_c^{\ell-1}(H)$ , the norm of the class of  $d(\chi \cdot \pi^*\theta)$  in  $L^q\overline{H}_{\text{dR}}^\ell(G)$  satisfies*

$$\| [d(\chi \cdot \pi^*\theta)] \|_{L^q\overline{H}^\ell(G)} \leq C \inf_{t \in \mathbb{R}} \{ \| (e^{t\delta})^* d\theta \|_{L^q\Omega^\ell(H)} + \| (e^{t\delta})^* \theta \|_{L^q\Omega^{\ell-1}(H)} \}.$$

**Proof** Since  $q > h/w_\ell$ , Lemma 3.1 shows that the assumptions of Theorem 2.5 are satisfied. By analyzing Step 1 in the proof of Theorem 2.5, and by using the homogeneity of  $G$ , one sees that there exists a constant  $C > 0$  such that for every  $\theta \in \Omega_c^{\ell-1}(H)$ ,

$$(3.5) \quad \| d(\chi \cdot \pi^*\theta) \|_{\Omega^{q,\ell}(G)} \leq C (\| d\theta \|_{L^q\Omega^\ell(H)} + \| \theta \|_{L^q\Omega^{\ell-1}(H)}).$$

The left translation by  $(t, 1_H)$ , which we denote by  $L_{(t,1_H)}$ , is an isometry of  $G$ . Therefore it acts by isometry on  $L^q\overline{H}_{\text{dR}}^\ell(G)$ . One has

$$L_{(t,1_H)}^*(d(\chi \cdot \pi^*\theta)) = d(\chi \circ \varphi_t \cdot \pi^*(e^{t\delta})^*\theta) = \varphi_t^*(d(\chi \cdot \pi^*(e^{t\delta})^*\theta)).$$

Thus, by Proposition 2.1, the forms  $L_{(t,1_H)}^*(d(\chi \cdot \pi^*\theta))$  and  $d(\chi \cdot \pi^*(e^{t\delta})^*\theta)$  are cohomologous in  $L^q\overline{H}_{\text{dR}}^\ell(G)$ . So the classes of  $d(\chi \cdot \pi^*\theta)$  and of  $d(\chi \cdot \pi^*(e^{t\delta})^*\theta)$  have equal norm. One obtains the proposition by applying inequality (3.5) to the  $(e^{t\delta})^*\theta$  terms. □

Proposition 3.4 provides upper bounds for norms of classes by means of norms of forms. These upper bounds on norms of forms can themselves be obtained thanks to the following lemma:

**Lemma 3.6** *Let  $H$  be a connected Lie group equipped with a left-invariant Riemannian metric, and let  $\mathfrak{h}$  be its Lie algebra. Let  $\delta \in \text{Der}(\mathfrak{h})$  be an  $\mathbb{R}$ -diagonalizable derivation of  $\mathfrak{h}$ . Then for every  $k \in \mathbb{N}$  the endomorphism  $\delta^* : \Lambda^k \mathfrak{h}^* \rightarrow \Lambda^k \mathfrak{h}^*$  is diagonalizable too. Let  $\{\omega_I\} \subset \Lambda^k \mathfrak{h}^*$  be a basis of eigenvectors, and denote by  $\mu_I \in \mathbb{R}$  the corresponding eigenvalues. By identifying  $\Lambda^k \mathfrak{h}^*$  with the space of left-invariant  $k$ -forms on  $H$ , every  $\omega \in \Omega^k(H)$  decomposes uniquely as  $\omega = \sum_I f_I \omega_I$ , where  $f_I \in \Omega^0(H)$ . One has*

$$\|(e^\delta)^* \omega\|_{L^p \Omega^k(H)} \asymp_D \sum_I e^{\mu_I - h/p} \|f_I\|_{L^p(H)},$$

where  $h$  is the trace of  $\delta$ , and  $D > 0$  is a constant which depends only on  $p$  and the choice of  $\{\omega_I\}$ .

**Proof** Since the norms on  $\Lambda^k \mathfrak{h}^*$  are all equivalent, there exists a constant  $C > 0$  such that for every  $\omega = \sum_I f_I \omega_I \in \Omega^k(H)$  and  $g \in H$ :

$$|\omega|_g \asymp_C \left( \sum_I |f_I(g)|^p \right)^{1/p}.$$

On the other hand,

$$(e^\delta)^* \omega = \sum_I (f_I \circ e^\delta) \cdot (e^\delta)^* \omega_I = \sum_I (f_I \circ e^\delta) \cdot e^{\mu_I} \omega_I.$$

Therefore,

$$\begin{aligned} \|(e^\delta)^* \omega\|_{L^p \Omega^k}^p &= \int_H |e^{\delta^*} \omega|_g^p d\text{vol}(g) \asymp_{C^p} \int_H \sum_I |e^{\mu_I} (f_I \circ e^\delta)(g)|^p d\text{vol}(g) \\ &= \int_H \sum_I e^{p\mu_I} |f_I(g)|^p \text{Jac}(e^{-\delta})(g) d\text{vol}(g) \\ &= \int_H \sum_I e^{p(\mu_I - h/p)} |f_I(g)|^p d\text{vol}(g) \\ &= \sum_I e^{p(\mu_I - h/p)} \|f_I\|_{L^p}^p, \end{aligned}$$

since the Jacobian of  $e^\delta$  is  $e^h$ . Thus,

$$\|(e^\delta)^* \omega\|_{L^p \Omega^k} \asymp_C \left( \sum_I e^{p(\mu_I - h/p)} \|f_I\|_{L^p}^p \right)^{1/p} \asymp_D \sum_I e^{\mu_I - h/p} \|f_I\|_{L^p},$$

where  $D$  depends only on  $p$  and  $\{\omega_I\}$ . □

## 4 Real hyperbolic spaces

We collect applications to a first series of concrete examples, namely real hyperbolic spaces. Let  $R = \mathbb{R} \rtimes_\delta \mathbb{R}^n$  with  $\delta = -\text{id}_{\mathbb{R}^n} \in \text{Der}(\mathbb{R}^n)$ . Then  $R$  is a solvable Lie group isometric to the real hyperbolic space  $\mathbb{H}_{\mathbb{R}}^{n+1}$ . Its cohomology admits the following rather simple description, which appears already in [Pansu 2008] (apart from the density statement).

**Theorem 4.1** For every  $k \in \{1, \dots, n\}$ , one has:

- (1)  $L^p H_{\text{dR}}^k(R) = \{0\}$  for  $1 < p < n/k$  or  $p > n/(k - 1)$ .
- (2) If  $n/k < p < n/(k - 1)$ , then  $L^p H_{\text{dR}}^k(R)$  is Hausdorff, and Banach isomorphic to  $\mathcal{L}^{p,k}(R, \xi)$ .  
The space  $\{\pi^* d\theta : \theta \in \Omega_c^{k-1}(\mathbb{R}^n)\}$  is dense in  $\mathcal{L}^{p,k}(R, \xi)$ ; in particular,  $L^p H_{\text{dR}}^k(R)$  is nonzero.

**Proof** For  $k \in \{1, \dots, n\}$  one has  $w_k = W_k = k$  and  $h = n$ . Item (1) comes from Theorem 3.2(1). Item (2) is an application of Theorem 3.2(2) and (3), in combination with Proposition 2.2. Indeed:

$$\lim_{t \rightarrow +\infty} \varphi_t^*(d(\chi \cdot \pi^* \theta)) = \lim_{t \rightarrow +\infty} d((\chi \circ \varphi_t) \cdot \pi^* \theta) = d\pi^* \theta = \pi^* d\theta,$$

in the sense of currents. □

We also obtain the following norm estimates. Recall from Proposition 2.4 that every  $\psi \in \mathcal{L}^{p,k}(R, \xi)$  can be written as  $\psi = \pi^* T$  for some (unique)  $T \in \mathcal{D}^k(\mathbb{R}^n)$ .

**Proposition 4.2** Let  $k \in \{1, \dots, n\}$ , let  $n/k < p < n/(k - 1)$ , and let  $(q, \ell)$  be the Poincaré dual of  $(p, k)$ . There exists some constant  $C > 0$  such that the norm of every current  $\pi^*(T) \in \mathcal{L}^{p,k}(R, \xi)$  satisfies

$$\|\pi^* T\|_{\Psi^{p,k}(R)} \asymp_C \sup\{T(\theta) : \theta \in \Omega_c^{\ell-1}(\mathbb{R}^n), \|\pi^* d\theta\|_{\Psi^{q,\ell}(R)} \leq 1\}.$$

Moreover, for  $\theta \in \Omega_c^{k-1}(\mathbb{R}^n)$ , the norm of the form  $\pi^* d\theta \in \mathcal{L}^{p,k}(R, \xi)$  satisfies

$$\|\pi^* d\theta\|_{\Psi^{p,k}(R)} \leq C \inf_{t \in \mathbb{R}} \{e^{-(k-n/p)t} \|d\theta\|_{L^p \Omega^k(\mathbb{R}^n)} + e^{(1-k+n/p)t} \|\theta\|_{L^p \Omega^{k-1}(\mathbb{R}^n)}\}.$$

Observe that the exponents in the last inequality satisfy  $k - n/p > 0$  and  $1 - k + n/p > 0$ .

**Proof** The spaces  $\mathcal{L}^{p,k}(R, \xi)$  and  $L^p H_{\text{dR}}^k(R)$  are Banach isomorphic by the map  $[\omega] \mapsto \omega_\infty$  of Proposition 2.2(2). Thus the form  $\pi^* d\theta \in \mathcal{L}^{p,k}(R, \xi)$  and the class  $[d(\chi \cdot \pi^* \theta)] \in L^p H_{\text{dR}}^k(R)$  have comparable norms. The inequalities follow then from Theorem 3.2(4), Proposition 3.4 and Lemma 3.6, applied with  $H = \mathbb{R}^n$  and  $\delta = -t \text{id}_{\mathbb{R}^n}$ . □

## 5 The groups $S_\alpha \in \mathcal{S}_{\text{straight}}^{2,3}$

We prove Theorem A (stated in the introduction), which determines the second  $L^p$ -cohomology of the groups  $S_\alpha \in \mathcal{S}_{\text{straight}}^{2,3}$ .

### 5.1 Reduction and decomposition

Let  $S_\alpha = \mathbb{R}^2 \rtimes_\alpha \mathbb{R}^3 \in \mathcal{S}_{\text{straight}}^{2,3}$ . We provide a somewhat “canonical” presentation of the group  $S_\alpha$  (see Proposition 5.2), which is then used to decompose  $S_\alpha$ .

Recall that precomposing  $\alpha$  with an element of  $\text{GL}_2(\mathbb{R})$ , or postcomposing with an element of the permutation group  $S_3$ , does not affect the isomorphism class of  $S_\alpha$ .

Let  $\{\varepsilon_1, \varepsilon_2\}$  denote the canonical basis of  $\mathbb{R}^2$ , and  $\{\varepsilon_1^*, \varepsilon_2^*\}$  its dual basis. By definition of the family  $\mathcal{G}_{\text{straight}}^{2,3}$ , the weights  $\varpi_1, \varpi_2, \varpi_3$  of  $\alpha$  generate  $(\mathbb{R}^2)^*$  and belong to a line disjoint from 0. By precomposing  $\alpha$  by an element of  $\text{GL}_2(\mathbb{R})$  and postcomposing by a permutation of the diagonal entries, if necessary, we can ensure that

- the  $\varpi_i$  belong to the vertical line  $\Delta$  passing through  $-\varepsilon_1^*$ ,
- they admit  $-\varepsilon_1^*$  as center of mass,
- the algebraic distances between them on  $\Delta$  (oriented by  $\varepsilon_2^*$ ) satisfy  $0 \leq \varpi_2 - \varpi_3 \leq \varpi_1 - \varpi_2$ ; ie  $\varpi_3, \varpi_2, \varpi_1$  lie in this order on  $\Delta$ , and  $\varpi_2$  is closer to  $\varpi_3$  than to  $\varpi_1$ .

In other words, there exist  $\mu_1, \mu_2, \mu_3 \in \mathbb{R}$ , not all equal, such that the weights can be written as  $\varpi_i = -\varepsilon_1^* + \mu_i \varepsilon_2^*$  for  $i = 1, 2, 3$ , with

$$(5.1) \quad \sum_{i=1}^3 \mu_i = 0 \quad \text{and} \quad 0 \leq \mu_2 - \mu_3 \leq \mu_1 - \mu_2.$$

To sum up the above reduction, we have established:

**Proposition 5.2** *There exists  $D_\mu = \text{diag}(\mu_1, \mu_2, \mu_3) \in \text{Diag}(\mathbb{R}^3)$ , a nonzero diagonal matrix, unique up to a positive multiplicative constant, enjoying the relations (5.1), such that, up to precomposition by an element of  $\text{GL}_2(\mathbb{R})$  and postcomposition by a permutation of the diagonal entries, the Lie group morphism  $\alpha$  can be written*

$$\alpha(t, s) = e^{-tI_3 + sD_\mu} \quad \text{for every } (t, s) \in \mathbb{R}^2.$$

Moreover, with the notation of Theorem A, one has

$$p_\alpha = 1 + \frac{\mu_1 - \mu_3}{\mu_1 - \mu_2}.$$

We assume from now on that the expression of  $\alpha$  is as in the previous proposition. Let consider the following subgroups of  $S_\alpha$ :

$$R := \mathbb{R} \ltimes_{-I_3} \mathbb{R}^3 \quad \text{and} \quad H_\mu := \mathbb{R} \ltimes_{D_\mu} \mathbb{R}^3.$$

The group  $R$  is naturally isometric to  $\mathbb{H}_{\mathbb{R}}^4$ . Let  $\mathfrak{r}$  and  $\mathfrak{h}_\mu$  be their Lie algebras. Let  $(0, D_\mu)$  and  $(0, -I_3)$  denote the derivations of  $\mathfrak{r}$  and  $\mathfrak{h}_\mu$  that trivially extend  $-I_3$  and  $D_\mu$ . Then  $S_\alpha$  admits two decompositions, namely

$$S_\alpha = \mathbb{R} \ltimes_{(0, D_\mu)} R \quad \text{and} \quad S_\alpha = \mathbb{R} \ltimes_{(0, -I_3)} H_\mu.$$

We denote again by  $\xi$  the left-invariant vector field on  $R$  carried by the  $\mathbb{R}$ -factor, and by  $\pi$  the projection map from  $R$  onto  $\mathbb{R}^3$ .

The proof of Theorem A will mainly rely on the decomposition  $S_\alpha = \mathbb{R} \ltimes_{(0, D_\mu)} R$ , in combination with the description of the  $L^p$ -cohomology of  $R \simeq \mathbb{H}_{\mathbb{R}}^4$  given in Theorem 4.1 and Proposition 4.2. We will

use the realization of de Rham  $L^p$ -cohomology by means of currents, which gives the Banach space isomorphism

$$L^p H_{\text{dR}}^2(R) \simeq \mathcal{E}^{p,2}(R, \xi),$$

where  $\mathcal{E}^{p,2}(R, \xi)$  is the space of closed 2-currents  $\psi$  on  $R$ , invariant under the flow  $(\varphi_t)$  of  $\xi$  and such that  $\|\psi\|_{\Psi^{p,2}} < +\infty$ . According to Proposition 2.4, every  $\psi \in \mathcal{E}^{p,2}(M, \xi)$  can be written  $\psi = \pi^*(T)$  for some  $T \in \mathcal{D}'^2(\mathbb{R}^3) \cap \text{Ker } d$ .

### 5.2 First cohomological observations

We derive from previous results some preliminary observations on  $L^p H_{\text{dR}}^2(S_\alpha)$ , whose statements do not depend on the morphism  $\alpha$ . The notation is the same as in the previous section.

**Proposition 5.3** *For  $p < \frac{3}{2}$ , we have the vanishing  $L^p H_{\text{dR}}^2(S_\alpha) = \{0\}$ , and for  $p \in (\frac{3}{2}; 3)$ , the cohomology space  $L^p H_{\text{dR}}^2(S_\alpha)$  is Hausdorff.*

**Proof** One has  $S_\alpha = \mathbb{R} \times_\delta H_\mu$ , with  $\delta = (0, -I_3) \in \text{Der}(\mathfrak{h}_\mu)$ . The ordered list of eigenvalues of  $-\delta$ , enumerated with multiplicity, is

$$\lambda_1 = 0 < \lambda_2 = \lambda_3 = \lambda_4 = 1.$$

With the notation of Section 3, the trace of  $-\delta$  is  $h = 3$ , and we have  $W_1 = \lambda_4 = 1$  and  $W_2 = \lambda_3 + \lambda_4 = 2$ . Therefore the statement follows from Theorem 3.2(1) and (2). □

**Proposition 5.4** *For  $p \in (\frac{3}{2}; 3)$ , the Banach space  $\mathcal{E}^{p,2}(R, \xi)$  is nonzero, and there exists a linear isomorphism*

$$L^p H_{\text{dR}}^2(S_\alpha) \simeq \left\{ \pi^* T \in \mathcal{E}^{p,2}(R, \xi) : \int_{\mathbb{R}} \|\pi^* e^{sD_\mu} T\|_{\Psi^{p,2}(R)}^p ds < +\infty \right\}.$$

**Proof** When  $p \in (\frac{3}{2}; 3)$ , Theorem 4.1 shows that  $L^p H_{\text{dR}}^2(R)$  is nonzero and Hausdorff, and that  $L^p H_{\text{dR}}^k(R) = \{0\}$  in all degrees  $k \neq 2$ . Since  $S_\alpha = \mathbb{R} \times_{(0, D_\mu)} R$ , the above description of the cohomology of  $R$ , in combination with a Hochschild–Serre spectral sequence argument (see [Bourdon and Rémy 2023, Corollary 6.10]), yields the linear isomorphism

$$L^p H_{\text{dR}}^2(S_\alpha) \simeq \left\{ [\omega] \in L^p H_{\text{dR}}^2(R) : \int_{\mathbb{R}} \|e^{s(0, D_\mu)^*} [\omega]\|_{L^p H^2(R)}^p ds < +\infty \right\}.$$

By Theorem 4.1(2), the Banach spaces  $L^p H_{\text{dR}}^2(R)$  and  $\mathcal{E}^{p,2}(R, \xi)$  are isomorphic. Moreover, every  $\psi \in \mathcal{E}^{p,2}(R, \xi)$  can be written  $\psi = \pi^*(T)$  for some  $T \in \mathcal{D}'^2(\mathbb{R}^3) \cap \text{Ker } d$ ; see Proposition 2.4. This leads to the desired linear isomorphism. □

**Proposition 5.5** *For  $p > 3$ , the space  $L^p H_{\text{dR}}^2(S_\alpha)$  is nonzero.*

**Proof** Consider again  $\lambda_1 = 0 < \lambda_2 = \lambda_3 = \lambda_4 = 1$  the list of the eigenvalues of  $-\delta = -(0, -I_3) \in \text{Der}(\mathfrak{h}_\mu)$ . The trace of  $-\delta$  is  $h = 3$ , and one has  $w_2 = \lambda_1 + \lambda_2 = 1$ . The rank of  $S_\alpha$  is equal to 2, so by [Bourdon and Rémy 2023, Theorem B and Corollary 3.4],  $L^p H_{\text{dR}}^2(S_\alpha)$  is nonzero for  $p > h/w_2 = 3$ . □

### 5.3 Nonvanishing of the second $L^p$ -cohomology

We wish to establish the nonvanishing part of Theorem A. Thanks to Proposition 5.5, we just need to prove that  $L^p H_{\text{dR}}^2(S_\alpha) \neq \{0\}$  for  $p \in (p_\alpha; 3)$ .

Assume  $p \in (\frac{3}{2}; 3)$ . By Proposition 5.4 there is a linear isomorphism

$$L^p H_{\text{dR}}^2(S_\alpha) \simeq \left\{ \pi^* T \in \mathcal{L}^{p,2}(R, \xi) : \int_{\mathbb{R}} \|\pi^* e^{sD_\mu} T\|_{\Psi^{p,2}(R)}^p ds < +\infty \right\}.$$

Recall from Theorem 4.1(2) that the space  $\mathcal{L}^{p,2}(R, \xi)$  contains the forms  $\pi^* d\theta$  with  $\theta \in \Omega_c^1(\mathbb{R}^3)$ . Therefore, in order to show that  $L^p H_{\text{dR}}^2(S_\alpha)$  is nonzero, it is enough to exhibit a nonzero form  $d\theta$  with  $\theta \in \Omega_c^1(\mathbb{R}^3)$  and  $\|\pi^* e^{sD_\mu} d\theta\|_{\Psi^{p,2}(R)} \rightarrow 0$  exponentially fast when  $s \rightarrow \pm\infty$ .

Let  $\theta$  be a smooth compactly supported 1-form on  $\mathbb{R}^3$ . From Proposition 4.2, with  $\theta$  replaced by  $e^{sD_\mu} \theta$ , we have

$$\|\pi^* e^{sD_\mu} d\theta\|_{\Psi^{p,2}(R)} \leq C \inf_{t \in \mathbb{R}} \left\{ e^{-(2-3/p)t} \|e^{sD_\mu} d\theta\|_{L^p \Omega^2(\mathbb{R}^3)} + e^{(-1+3/p)t} \|e^{sD_\mu} \theta\|_{L^p \Omega^1(\mathbb{R}^3)} \right\}.$$

Write  $\theta = f dx + g dy + h dz$ , so that  $d\theta = F dy \wedge dz + G dx \wedge dz + H dx \wedge dy$ . Since the trace of  $D_\mu$  is zero, Lemma 3.6 applied with  $H = \mathbb{R}^3$  and  $\delta = D_\mu = \text{diag}(\mu_1, \mu_2, \mu_3)$  gives the estimates

$$\begin{aligned} \|e^{sD_\mu} d\theta\|_{L^p \Omega^2} &\asymp e^{-s\mu_1} \|F\|_{L^p} + e^{-s\mu_2} \|G\|_{L^p} + e^{-s\mu_3} \|H\|_{L^p}, \\ \|e^{sD_\mu} \theta\|_{L^p \Omega^1} &\asymp e^{s\mu_1} \|f\|_{L^p} + e^{s\mu_2} \|g\|_{L^p} + e^{s\mu_3} \|h\|_{L^p}. \end{aligned}$$

We denote by  $\alpha_\pm$  the exponent of the leading term in the asymptotics of  $\|e^{sD_\mu} d\theta\|$  when  $s \rightarrow \pm\infty$ , namely  $\|e^{sD_\mu} d\theta\| \asymp_{s \rightarrow \pm\infty} e^{\alpha_\pm s}$ ; note that  $\alpha_+$  and  $\alpha_-$  are opposites of diagonal coefficients of  $D_\mu$  since  $\text{trace}(D_\mu) = 0$ . Similarly, we denote by  $\beta_\pm$  the exponent of the leading term in the asymptotics of  $\|e^{sD_\mu} \theta\|$  when  $s \rightarrow \pm\infty$ , namely  $\|e^{sD_\mu} \theta\| \asymp_{s \rightarrow \pm\infty} e^{\beta_\pm s}$ ; note that  $\beta_+$  and  $\beta_-$  are diagonal coefficients of the matrix  $D_\mu$ . One has:

**Lemma 5.6** *Let  $a, b > 0$  be positive real numbers and let  $\alpha, \beta \in \mathbb{R}$ . We assume that  $A = A(s) \asymp e^{\alpha s}$  and  $B = B(s) \asymp e^{\beta s}$  when  $s \rightarrow +\infty$  (resp. when  $s \rightarrow -\infty$ ). Then*

$$\inf_{t \in \mathbb{R}} \{e^{-at} A + e^{bt} B\} \asymp e^{\frac{a\beta + b\alpha}{a+b} s}$$

when  $s \rightarrow +\infty$  (resp. when  $s \rightarrow -\infty$ ). In particular, the infimum tends to 0 if and only if we have  $(a\beta + b\alpha)s \rightarrow -\infty$  when  $s \rightarrow +\infty$  (resp. when  $s \rightarrow -\infty$ ); in which case the speed of convergence to 0 is exponential.

**Proof** Assume first that  $A, B > 0$  are fixed and consider the function  $f$  defined by  $f(t) = e^{-at} A + e^{bt} B$ . We have  $\lim_{t \rightarrow \pm\infty} f(t) = +\infty$  so  $f$  achieves its minimum at a point  $t_{\min}$  such that  $f'(t_{\min}) = 0$ . Since  $f'(t) = -ae^{-at} A + be^{bt} B$ , we have  $A/B = (b/a)e^{(a+b)t_{\min}}$  and therefore the minimal value of  $f$  is

$$f(t_{\min}) = B e^{bt_{\min}} \left( \frac{A}{B} e^{-(a+b)t_{\min}} + 1 \right) = B e^{bt_{\min}} \left( \frac{b}{a} + 1 \right).$$

When  $A \asymp e^{\alpha s}$  and  $B \asymp e^{\beta s}$ , we have  $e^{(\alpha-\beta)s} \asymp A/B = (b/a)e^{(a+b)t_{\min}}$ . Then

$$f(t_{\min}) \asymp e^{\beta s} e^{b t_{\min}} \asymp e^{(\beta + b \frac{\alpha - \beta}{a + b})s} = e^{\frac{a\beta + b\alpha}{a + b}s}. \quad \square$$

For  $p \in (\frac{3}{2}; 3)$ , with  $a = 2 - 3/p$  and  $b = -1 + 3/p$  in the above lemma, when  $s \rightarrow \pm\infty$  we obtain the estimate

$$\|\pi^* e^{sD_\mu} d\theta\|_{\Psi^{p,2}(\mathbb{R})} \lesssim e^{\frac{a\beta_\pm + b\alpha_\pm}{a+b}s} = e^{\{(2p-3)\beta_\pm + (-3+p)\alpha_\pm\} \frac{s}{p}}.$$

This shows that for the condition  $\int_{\mathbb{R}} \|\pi^* e^{sD_\mu} T\|_{\Psi^{p,2}(\mathbb{R})}^p ds < +\infty$  to be satisfied by  $T = d\theta$ , it is sufficient to have

$$(5.7) \quad (2p - 3)\beta_+ + (3 - p)\alpha_+ < 0 \quad \text{and} \quad (2p - 3)\beta_- + (3 - p)\alpha_- > 0.$$

To exhibit such a form  $d\theta$ , we will use:

**Lemma 5.8** *There exist forms  $\theta = f dx$  and  $\Theta = g dy + h dz$  in  $\Omega_c^1(\mathbb{R}^3)$  such that*

$$d\theta = d\Theta = G dx \wedge dz + H dx \wedge dy \neq 0.$$

**Proof** Let  $u$  be an arbitrary nonzero function in  $\Omega_c^0(\mathbb{R}^3)$ . Its differential is

$$du = \frac{\partial u}{\partial x} dx + \frac{\partial u}{\partial y} dy + \frac{\partial u}{\partial z} dz.$$

Set  $\theta := (\partial u / \partial x) dx$  and  $\Theta := -(\partial u / \partial y) dy - (\partial u / \partial z) dz$ . Since  $d du = 0$ , one has

$$d\theta = d\Theta = -\frac{\partial^2 u}{\partial x \partial z} dx \wedge dz - \frac{\partial^2 u}{\partial x \partial y} dx \wedge dy. \quad \square$$

Let  $d\theta = d\Theta$  be as in the previous lemma. From the relations (5.1) we have  $\alpha_+ = -\mu_3$  and  $\alpha_- = -\mu_2$ . Similarly we have  $\beta_- = \beta_-(\theta) = \mu_1$  and  $\beta_+ = \beta_+(\Theta) = \mu_2$ . When  $s \rightarrow +\infty$ , the integrability conditions (5.7) and the relations (5.1) lead to the condition

$$(2p - 3)\mu_2 - (3 - p)\mu_3 < 0,$$

hence  $p(2\mu_2 + \mu_3) - 3\mu_2 - 3\mu_3 < 0$ , that is  $p(\mu_2 - \mu_1) + 3\mu_1 > 0$ , amounting to

$$p > \frac{3\mu_1}{\mu_1 - \mu_2} = 1 + \frac{\mu_1 - \mu_3}{\mu_1 - \mu_2} = p_\alpha.$$

When  $s \rightarrow -\infty$ , they lead to

$$(2p - 3)\mu_1 - (3 - p)\mu_2 > 0,$$

hence  $p(2\mu_1 + \mu_2) - 3\mu_1 - 3\mu_2 > 0$ , that is  $p(\mu_1 - \mu_3) + 3\mu_3 > 0$ , amounting to

$$p > \frac{-3\mu_3}{\mu_1 - \mu_3} = 1 + \frac{\mu_2 - \mu_3}{\mu_1 - \mu_3}.$$

The latter condition is implied by the former one, since  $1 + (\mu_2 - \mu_3)/(\mu_1 - \mu_3) \in [1; \frac{3}{2}]$  and  $p_\alpha \in [2; 3]$ . To sum up, we have shown that  $L^p H_{\mathbb{R}}^2(S_\alpha) \neq \{0\}$  for  $p \in (p_\alpha; 3)$ , as expected.

### 5.4 Vanishing of the second $L^p$ -cohomology

It remains to prove the vanishing statement in Theorem A. It will be obtained by using a Poincaré duality argument, together with some estimates similar to those from the nonvanishing part.

According to Proposition 5.3, it is enough to consider the case  $p \in (\frac{3}{2}; 3)$ . We start again from the identification given in Proposition 5.4:

$$L^p H_{\text{dR}}^2(S_\alpha) \simeq \left\{ \pi^* T \in \mathcal{L}^{p,2}(R, \xi) : \int_{\mathbb{R}} \|\pi^* e^{sD_\mu} T\|_{\Psi^{p,2}(R)}^p ds < +\infty \right\}.$$

To show that  $L^p H_{\text{dR}}^2(S_\alpha)$  vanishes, it is enough to prove that every  $\pi^* T \in \mathcal{L}^{p,2}(R, \xi)$  satisfies

$$\|\pi^* e^{sD_\mu} T\|_{\Psi^{p,2}(R)} \rightarrow +\infty \quad \text{when } s \rightarrow +\infty \text{ or when } s \rightarrow -\infty.$$

Recall from Proposition 4.2 that

$$\|\pi^* T\|_{\Psi^{p,2}(R)} \asymp \sup\{T(\theta) : \theta \in \Omega_c^1(\mathbb{R}^3), \|\pi^* d\theta\|_{\Psi^{q,2}(R)} \leq 1\},$$

where  $q$  denotes the Hölder conjugate of  $p$ . When replacing  $\pi^* T$  by  $\pi^* e^{sD_\mu} T$  with  $s \in \mathbb{R}$ , a change of variable provides

$$\|\pi^* e^{sD_\mu} T\|_{\Psi^{p,2}(R)} \asymp \sup\{T(\theta) : \theta \in \Omega_c^1(\mathbb{R}^3), \|\pi^* e^{sD_\mu} d\theta\|_{\Psi^{q,2}(R)} \leq 1\}.$$

By Proposition 4.2, with  $\theta$  replaced by  $e^{sD_\mu} \theta$ , we obtain

$$\|\pi^* e^{sD_\mu} d\theta\|_{\Psi^{q,2}(R)} \leq C \inf_{t \in \mathbb{R}} \left\{ e^{-(3/p-1)t} \|e^{sD_\mu} d\theta\|_{L^q \Omega^2(\mathbb{R}^3)} + e^{(2-3/p)t} \|e^{sD_\mu} \theta\|_{L^q \Omega^1(\mathbb{R}^3)} \right\},$$

where, in the upper bound, the coefficients in the exponentials in front of the norms come from the identity

$$2 - \frac{3}{q} = \frac{3}{p} - 1 \quad \text{and} \quad -1 + \frac{3}{q} = 2 - \frac{3}{p}.$$

Using Lemma 5.6 with  $a = 3/p - 1$  and  $b = 2 - 3/p$ , and keeping the notation  $\alpha_\pm$  and  $\beta_\pm$  defined after replacing  $L^p$  norms by  $L^q$  norms, we obtain

$$(5.9) \quad \|\pi^* e^{sD_\mu} d\theta\|_{\Psi^{q,2}(R)} \lesssim e^{(a\beta_\pm + b\alpha_\pm)s} \quad \text{when } s \rightarrow \pm\infty.$$

These observations lead to:

**Lemma 5.10** *Let  $\pi^* T \in \mathcal{L}^{p,2}(R, \xi)$ , and let  $T = T_1 dy \wedge dz + T_2 dx \wedge dz + T_3 dx \wedge dy$  be its writing in the canonical global coordinates of  $\mathbb{R}^3$ , with  $T_i \in \mathcal{D}^0(\mathbb{R}^3)$ .*

- (i) *If  $T_1 \neq 0$ , then  $\lim_{s \rightarrow -\infty} \|\pi^* e^{sD_\mu} T\|_{\Psi^{p,2}(R)} = +\infty$ .*
- (ii) *If  $T_3 \neq 0$  and if  $p < p_\alpha$ , then  $\lim_{s \rightarrow +\infty} \|\pi^* e^{sD_\mu} T\|_{\Psi^{p,2}(R)} = +\infty$ .*

**Proof** (i) Let  $\theta$  be of the form  $\theta = f dx$  with  $f$  a smooth compactly supported function such that  $T_1(f) = 1$ . Then  $T(\theta) = T_1(f) = 1$ . We have  $d\theta = -(\partial f/\partial y) dx \wedge dy - (\partial f/\partial z) dx \wedge dz$ . Therefore with the relations (5.1), one has  $\alpha_- = -\mu_2$  and  $\beta_- = \mu_1$ . We consider the quantity

$$p(a\beta_- + b\alpha_-) = (3 - p)\mu_1 - (2p - 3)\mu_2 = -p(\mu_2 - \mu_3) - 3\mu_3.$$

Since  $p \in (\frac{3}{2}; 3)$  and since  $\mu_3 \leq \mu_2 \leq 0$ , one has  $-p(\mu_2 - \mu_3) - 3\mu_3 \geq -3\mu_2 \geq 0$ . We deduce that  $a\beta_- + b\alpha_- > 0$ . Relation (5.9) then implies that  $\lim_{s \rightarrow -\infty} \|\pi^* e^{sD\mu^*} d\theta\|_{\Psi^{q,2}(R)} = 0$ , hence that  $\lim_{s \rightarrow -\infty} \|\pi^* e^{sD\mu^*} T\|_{\Psi^{p,2}(R)} = +\infty$ .

(ii) Let  $\theta$  be of the form  $\theta = h dz$ , with  $h$  a smooth compactly supported function such that  $T_3(h) = 1$ . Then  $T(\theta) = T_3(h) = 1$ . We have  $d\theta = \frac{\partial h}{\partial x} dx \wedge dz + \frac{\partial h}{\partial y} dy \wedge dz$ . Thus  $\alpha_+ = -\mu_2$  and  $\beta_+ = \mu_3$ . We consider the quantity

$$p(a\beta_+ + b\alpha_+) = (3 - p)\mu_3 - (2p - 3)\mu_2 = p(\mu_1 - \mu_2) - 3\mu_1.$$

One has  $a\beta_+ + b\alpha_+ < 0$  if and only if

$$p < \frac{3\mu_1}{\mu_1 - \mu_2} = 1 + \frac{\mu_1 - \mu_3}{\mu_1 - \mu_2} = p_\alpha.$$

Thus for  $p < p_\alpha$ , we have  $a\beta_+ + b\alpha_+ < 0$ . Relation (5.9) implies  $\lim_{s \rightarrow +\infty} \|\pi^* e^{sD\mu^*} d\theta\|_{\Psi^{q,2}(R)} = 0$ , hence that  $\lim_{s \rightarrow +\infty} \|\pi^* e^{sD\mu^*} T\|_{\Psi^{p,2}(R)} = +\infty$ . □

**Proof that  $L^p H_{\text{dR}}^2(S_\alpha) = \{0\}$  for  $p \in (\frac{3}{2}; p_\alpha)$**  Let  $\pi^* T \in \mathcal{X}^{p,2}(R, \xi)$  be in correspondence with a class  $[\omega]$  in  $L^p H_{\text{dR}}^2(S_\alpha)$ . By items (i) and (ii) of the previous lemma, we must have  $T_1 = T_3 = 0$ . Thus  $T = T_2 dx \wedge dz$ . Since  $T$  is closed, we get that  $\partial T_2/\partial y = 0$ ; therefore  $T$ , and hence  $[\omega]$ , are invariant by the 1-parameter group  $(\tau_t)_{t \in \mathbb{R}}$  of translations along the  $y$ -axis. This in turn implies that  $[\omega] = 0$ , because  $\omega$  is  $L^p$ -integrable. To see this, suppose by contradiction that  $[\omega] \neq 0$ . Recall by Proposition 5.3 that  $L^p H_{\text{dR}}^2(S_\alpha)$  is Hausdorff. Then, by Poincaré duality, there exists  $[\varphi] \in L^q H_{\text{dR}}^3(S_\alpha)$  such that  $\int_{S_\alpha} \omega \wedge \varphi = 1$ . But  $[\tau_t^*(\omega)] = [\omega]$ , thus we get the following contradiction:

$$1 = \int_{S_\alpha} \tau_t^*(\omega) \wedge \varphi \rightarrow 0 \quad \text{when } t \rightarrow \infty,$$

since the supports of  $\tau_t^*(\omega)$  and of  $\varphi$  become more and more disjoint as  $t$  tends to  $\infty$ . □

## 6 Complex hyperbolic spaces

Another family of concrete examples for which a strip decomposition as stated in Theorem 3.2 can be derived is provided by the so-called complex hyperbolic spaces. Theorem 6.1 below describes the regions where the cohomology vanishes or does not. It also states that the cohomology is Hausdorff. The proof of the (non)vanishing statement relies on Theorem 3.2, in combination with some additional analysis

on Heisenberg groups that is developed in Section 6.1. The Hausdorff statement is a deep result due to Pansu [2011, Théorème 1]. We refer to his paper for a proof. The section ends with some complementary results (Propositions 6.7 and 6.11) that provide a finer description of the cohomology.

Let  $\text{Heis}(2m - 1)$  be the Heisenberg group of dimension  $2m - 1$  for some  $m \geq 2$ , ie the simply connected nilpotent Lie group whose Lie algebra  $\mathfrak{n}$  admits

$$X_1, \dots, X_{m-1}, Y_1, \dots, Y_{m-1}, Z$$

as a basis, and where the only nontrivial relations between the above generators are  $[X_i, Y_i] = Z$  for all  $i \in \{1, \dots, m - 1\}$ . Let  $R = \mathbb{R} \rtimes_{\delta} N$  with  $N = \text{Heis}(2m - 1)$  and  $\delta = -\text{diag}(1, \dots, 1, 2) \in \text{Der}(\mathfrak{n})$ . Then  $R$  is a solvable Lie group isometric to the complex hyperbolic space  $\mathbb{H}_{\mathbb{C}}^m$ .

Apart from the density statement and the (non)vanishing statement in items (2) and (3) (when  $m \geq 3$ ), the following result already appears in [Pansu 1999; 2011].

**Theorem 6.1** *Let  $k \in \{1, \dots, 2m - 1\}$ . One has:*

- (1)  $L^p H_{\text{dR}}^k(R) = \{0\}$  for  $1 < p < 2m/(k + 1)$  or  $p > 2m/(k - 1)$ .
- (2) If  $2m/(k + 1) < p < 2m/k$ , then  $L^p H_{\text{dR}}^k(R)$  is Hausdorff and Banach isomorphic to  $\mathcal{L}^{p,k}(R, \xi)$ . Moreover,  $L^p H_{\text{dR}}^k(R) \neq \{0\}$  if and only if  $k \geq m$ .
- (3) If  $2m/k < p < 2m/(k - 1)$ , then  $L^p H_{\text{dR}}^k(R)$  is Hausdorff and the classes of the forms  $d(\chi \cdot \pi^* \theta)$ , where  $\theta \in \Omega_c^{k-1}(N)$ , form a dense subspace. Moreover,  $L^p H_{\text{dR}}^k(R) \neq \{0\}$  if and only if  $k \leq m$ .

We notice that the above statement will be extended in Section 6.2: Proposition 6.7 will describe the zero-elements among the classes  $[d(\chi \cdot \pi^* \theta)]$ , while Proposition 6.11 will exhibit a natural dense subspace in  $\mathcal{L}^{p,k}(R, \xi)$ .

**Beginning of proof of Theorem 6.1** For  $k \in \{0, \dots, 2m - 2\}$ , one has  $h = 2m$ ,  $w_k = k$  and  $w_{2m-1} = h \geq 2m - 1$ . Similarly,  $W_k = k + 1$  for  $k \in \{1, \dots, 2m - 1\}$  and  $W_0 = 0 \leq 1$ . Item (1) comes from Theorem 3.2(1). The first part of item (2) follows from Theorem 3.2(2). The Hausdorff statement in item (3) is a deep theorem of Pansu [2011, Théorème 1]<sup>3</sup> when  $k \in \{2, \dots, m\}$ . This, in combination with Poincaré duality as stated in Proposition 1.1(1), proves the Hausdorff statement when  $k \in \{m + 1, \dots, 2m - 1\}$ . For  $k = 1$ , it follows from the fact that the group  $R$  is nonunimodular; see [Pansu 2007] and [Cornulier and Tessera 2011]. Finally, the density property follows from Theorem 3.2(3).

It remains to establish the (non)vanishing parts of items (2) and (3). It will require more material, and the proof will be completed only at the end of Section 6.1. □

<sup>3</sup>The proof of [Pansu 2011, Théorème 1] is independent of the invariance of the cup-product under quasi-isometries, whose proof needs more detail (according to Pansu).

### 6.1 Differential forms on the Heisenberg group

We complete the proof of the (non)vanishing statements in Theorem 6.1. They rely on Lemmas 6.3 and 6.5 below. The material is inspired by Rumin’s paper [1994].

Recall that  $\mathfrak{n}$  denotes the Lie algebra of  $N = \text{Heis}(2m - 1)$ . It decomposes as  $\mathfrak{n} = \mathfrak{n}_1 \oplus \mathfrak{n}_2$ , where  $\mathfrak{n}_1 := \text{Span}(X_1, \dots, X_{m-1}, Y_1, \dots, Y_{m-1})$  and  $\mathfrak{n}_2 := \text{Span}(Z)$  are, respectively, the eigenspaces of  $-\delta$  corresponding to the eigenvalues 1 and 2.

Let  $x_1, \dots, x_{m-1}, y_1, \dots, y_{m-1}, z$  be the coordinates on  $N$  induced by the exponential map  $\mathfrak{n} \rightarrow N$ . Let  $\tau := dz - \frac{1}{2} \sum_{i=1}^{m-1} (x_i dy_i - y_i dx_i)$ . We identify  $\mathfrak{n}^*$  with the space of the left-invariant 1-forms on  $N$ . One has  $\mathfrak{n}^* = \mathfrak{n}_1^* \oplus \mathfrak{n}_2^*$ , where  $\mathfrak{n}_1^* := \text{Span}(dx_1, \dots, dx_{m-1}, dy_1, \dots, dy_{m-1})$  and  $\mathfrak{n}_2^* := \text{Span}(\tau)$  are the eigenspaces of  $-\delta$  of eigenvalues 1 and 2.

The form  $d\tau = -\sum_{i=1}^{m-1} dx_i \wedge dy_i$  is a symplectic form when restricted to  $\mathfrak{n}_1$ . The Lefschetz map

$$(6.2) \quad L_k : \wedge^k \mathfrak{n}_1^* \rightarrow \wedge^{k+2} \mathfrak{n}_1^*, \quad \alpha \mapsto \alpha \wedge d\tau,$$

is therefore injective for  $k \leq m - 2$  and surjective for  $k \geq m - 2$ ; see [Bryant et al. 2003, Proposition 1.1].

The weight decomposition  $\wedge^k \mathfrak{n}^* = \wedge^k \mathfrak{n}_1^* \oplus \wedge^{k-1} \mathfrak{n}_1^* \wedge \tau$  associated to  $-\delta$  yields a decomposition

$$\Omega^k(N) = \Omega_1^k \oplus \Omega_2^k,$$

with  $\Omega_2^k = \Omega_1^{k-1} \wedge \tau$ . Therefore, every  $\theta \in \Omega^k(N)$  decomposes uniquely as

$$\theta = \theta_1 + \theta_2 \wedge \tau, \quad \text{with } \theta_1 \in \Omega_1^k \text{ and } \theta_2 \in \Omega_1^{k-1}.$$

The form  $\theta_1$  is said to be *horizontal* and of *pure weight*  $k$ . The form  $\theta_2 \wedge \tau$  is said to be *vertical* and of *pure weight*  $k + 1$ . We will use the indices  $_1$  and  $_2$  to specify the components of differential forms according to the above direct sum.

When  $2m/k < p < 2m/(k - 1)$ , and according to what we have already proved for Theorem 6.1(3), the space  $L^p H_{\text{dR}}^k(R)$  is Hausdorff and contains the dense subspace  $\{[d(\chi \cdot \pi^* \theta)] : \theta \in \Omega_c^{k-1}(N)\}$ . One has in addition:

**Lemma 6.3** *Suppose  $k \in \{2, \dots, 2m - 1\}$  and  $2m/k < p < 2m/(k - 1)$ .*

- (1) *Let  $\theta \in \Omega_c^{k-1}(N)$ . If  $\theta = \alpha \wedge d\tau + \beta \wedge \tau$ , with  $\alpha \in \Omega_c^{k-3}(N)$  and  $\beta \in \Omega_c^{k-2}(N)$ , then  $[d(\chi \cdot \pi^* \theta)] = 0$  in  $L^p H_{\text{dR}}^k(R)$ .*
- (2) *For  $k \geq m + 1$ , one has  $L^p H_{\text{dR}}^k(R) = \{0\}$ .*

**Proof** (1) Suppose first that  $\theta = \beta \wedge \tau$ . Since  $p > 2m/k \geq h/w_k$ , Proposition 3.4 implies that

$$\|[d(\chi \cdot \pi^* \theta)]\|_{L^p H^k(R)} \leq C \inf_{t \in \mathbb{R}} \{ \|(e^{t\delta})^* \theta\|_{L^p \Omega^{k-1}(N)} + \|(e^{t\delta})^* d\theta\|_{L^p \Omega^k(N)} \}.$$

Since  $\theta$  is of pure weight  $k$ , one has  $\|(e^{t\delta})^*\theta\|_{L^p\Omega^{k-1}} \asymp e^{(-k+2m/p)t}$  by Lemma 3.6. The weight of  $d\theta$  is at least  $k$ , thus for  $t \geq 0$  one has  $\|(e^{t\delta})^*d\theta\|_{L^p\Omega^k} \lesssim e^{(-k+2m/p)t}$ . Therefore  $\|[d(\chi \cdot \pi^*\theta)]\|_{L^p\mathbb{H}^k} \rightarrow 0$  when  $t \rightarrow +\infty$ , and thus  $[d(\chi \cdot \pi^*\theta)] = 0$  in  $L^p\mathbb{H}_{\text{dR}}^k(R)$ .

Now suppose that  $\theta = \alpha \wedge d\tau$ . We claim that there exists  $\gamma \in \Omega_c^{k-1}(N)$  such that  $d\theta = d(\gamma \wedge \tau)$ . By Corollary 2.6, this will imply that  $[d(\chi \cdot \pi^*\theta)] = [d(\chi \cdot \pi^*(\gamma \wedge \tau))]$ , which in turn implies that  $[d(\chi \cdot \pi^*\theta)] = 0$  from the previous case. Let  $\gamma := -(-1)^{d^\circ\alpha} d\alpha$ . One has

$$d(\theta - \gamma \wedge \tau) = d\alpha \wedge d\tau + (-1)^{d^\circ\alpha+1}(-1)^{d^\circ\alpha} d\alpha \wedge d\tau = 0,$$

and so  $d\theta = d(\gamma \wedge \tau)$ .

(2) Let  $\theta \in \Omega_c^{k-1}(N)$ . Since the Lefschetz map  $L_i$ , defined in (6.2), is surjective for  $i \geq m - 2$ , one can write the weight decomposition of  $\theta$  as

$$\theta = \alpha \wedge d\tau + \theta_2 \wedge \tau.$$

Therefore item (1) implies that  $[d(\chi \cdot \pi^*\theta)] = 0$  in  $L^p\mathbb{H}_{\text{dR}}^k(R)$ . This in turn implies that  $L^p\mathbb{H}_{\text{dR}}^k(R) = \{0\}$ , thanks to the density of the classes  $[d(\chi \cdot \pi^*\theta)]$ .  $\square$

The weight decomposition of  $k$ -forms can be extended to  $k$ -currents. This induces a decomposition

$$\mathcal{D}^k(N) = \mathcal{D}_1^k \oplus \mathcal{D}_2^k,$$

with  $\mathcal{D}_2^k = \mathcal{D}_1^{k-1} \wedge \tau$ . Concretely, every  $T \in \mathcal{D}^k$  can be written uniquely as

$$T = \sum_{|I|=|J|=k} T_{IJ} dx_I \wedge dy_J + \sum_{|K|+|L|=k-1} T_{KL} dx_K \wedge dy_L \wedge \tau,$$

with  $T_{IJ}, T_{KL} \in \mathcal{D}^0(N)$ . Its weight decomposition is then  $T = T_1 + T_2 \wedge \tau$ , with

$$T_1 = \sum_{|I|+|J|=k} T_{IJ} dx_I \wedge dy_J \quad \text{and} \quad T_2 = \sum_{|K|+|L|=k-1} T_{KL} dx_K \wedge dy_L.$$

The current  $T_1$  is said to be *horizontal*, and  $T_2 \wedge \tau$  to be *vertical*. For  $\theta \in \Omega_c^{2m-1-k}(N)$ , which weight-decomposes as  $\theta = \theta_1 + \theta_2 \wedge \tau$ , one shows easily that

$$(6.4) \quad T(\theta) = T_1(\theta_2 \wedge \tau) + T_2(\tau \wedge \theta_1).$$

From Theorem 6.1(2),  $L^p\mathbb{H}_{\text{dR}}^k(R)$  is Banach isomorphic to  $\mathcal{X}^{p,k}(R, \xi)$  for every  $k \in \{1, \dots, 2m - 1\}$  and  $2m/(k + 1) < p < 2m/k$ . Moreover, we know from Proposition 2.4 that every  $\psi \in \mathcal{X}^{p,k}(R, \xi)$  can be written as  $\psi = \pi^*T$  for some (unique)  $T \in \mathcal{D}^k(N)$ . One has, furthermore:

**Lemma 6.5** *Let  $k \in \{1, \dots, 2m - 1\}$  and  $2m/(k + 1) < p < 2m/k$ .*

- (1) *For every  $\pi^*T \in \mathcal{X}^{p,k}(R, \xi)$  the  $k$ -current  $T$  is vertical.*
- (2) *Conversely, if  $\varphi \in \Omega_c^{k-1}(N)$  is such that  $d\varphi$  is vertical, then  $\pi^*(d\varphi)$  belongs to  $\mathcal{X}^{p,k}(R, \xi)$ .*
- (3)  *$\mathcal{X}^{p,k}(R, \xi) \neq \{0\}$  for every  $k \in \{m, \dots, 2m - 1\}$ .*

**Proof** (1) Every  $T \in \mathcal{D}'^{2m-1}(N)$  is vertical, thus we can assume that  $k \in \{1, \dots, 2m - 2\}$ . Let  $(q, \ell)$  be the Poincaré dual of  $(p, k)$  relative to  $R$ ; it satisfies  $\ell \in \{2, \dots, 2m - 1\}$  and  $2m/\ell < q < 2m/(\ell - 1)$ . For every  $\pi^*T \in \mathcal{L}^{p,k}(R, \xi)$  and every vertical  $\theta \in \Omega_c^{\ell-1}(N)$ , one has  $T(\theta) = 0$ , thanks to Theorem 3.2 and Lemma 6.3. According to relation (6.4), this implies that the weight decomposition of  $T$  satisfies  $T_1 = 0$ . Thus  $T$  is vertical.

(2) Let  $\varphi \in \Omega_c^{k-1}(N)$  be such that  $d\varphi$  is vertical. First, we claim  $d(\chi \cdot \pi^* \varphi)$  belongs to  $\Omega^{p,k}(R) \cap \text{Ker } d$ . One has  $d(\chi \cdot \pi^* \varphi) = d\chi \wedge \pi^* \varphi + \chi \cdot \pi^* d\varphi$ . Thus

$$\|d(\chi \cdot \pi^* \varphi)\|_{\Omega^{p,k}} = \|d(\chi \cdot \pi^* \varphi)\|_{L^p \Omega^k} \leq \|d\chi \wedge \pi^* \varphi\|_{L^p \Omega^k} + \|\chi \cdot \pi^* d\varphi\|_{L^p \Omega^k}.$$

The form  $d\chi \wedge \pi^* \varphi$  is compactly supported, thus it belongs to  $L^p \Omega^k(R)$ . One has

$$\|\chi \cdot \pi^* d\varphi\|_{L^p \Omega^k(R)}^p \leq \|\mathbf{1}_{t \geq 0} \cdot \pi^* d\varphi\|_{L^p \Omega^k(R)}^p = \int_0^{+\infty} \|(e^{t\delta})^* d\varphi\|_{L^p \Omega^k(N)}^p dt.$$

Since  $d\varphi$  is vertical, it is of pure weight  $k + 1$ , and  $\|(e^{t\delta})^* d\varphi\|_{L^p \Omega^k(N)} \asymp e^{(-k-1+2m/p)t}$  by Lemma 3.6. Since  $p > 2m/(k + 1)$ , the above integral converges and the claim is proved.

One has  $\pi^* d\varphi = \lim_{t \rightarrow +\infty} \varphi_t^*(d(\chi \cdot \pi^* \varphi))$  in the sense of currents; thus,  $\pi^*(d\varphi) \in \mathcal{L}^{p,k}(R, \xi)$  by Proposition 2.2.

(3) It remains to show that there exists  $\varphi \in \Omega_c^k(N)$  such that  $d\varphi$  is vertical and nonzero. We distinguish the cases  $k > m$  and  $k = m$ .

Suppose  $k > m$ . Then  $\text{Ker}(L_{k-2}: \wedge^{k-2} \mathfrak{n}_1^* \rightarrow \wedge^k \mathfrak{n}_1^*)$  is nonzero. Let  $\alpha \in \Omega_1^{k-2}$  be nonzero, compactly supported and such that  $\alpha \wedge d\tau = 0$ . For every  $f \in \Omega_c^0(N)$ , consider the form  $\varphi = f \cdot \alpha \wedge \tau$ . Then  $d\varphi$  is vertical. Moreover,  $d\varphi \neq 0$  for generic  $f$ . Indeed, the form  $\alpha \wedge \tau$  is nonzero (since  $\alpha$  is horizontal and nonzero); and for any given nonzero form  $\beta$  of smaller degree than the dimension, the forms  $f \cdot \beta$  are nonclosed for generic  $f$ .

Assume now that  $k = m$ . Then the map  $L_{m-2}: \wedge^{m-2} \mathfrak{n}_1^* \rightarrow \wedge^m \mathfrak{n}_1^*$  is an isomorphism. Pick any compactly supported  $\varphi_1 \in \Omega_1^{m-1}$ . Let  $\varphi_2 \in \Omega_1^{m-2}$  be the unique solution of the equation

$$(6.6) \quad (d\varphi_1)_1 = -(-1)^m \varphi_2 \wedge d\tau,$$

and set  $\varphi := \varphi_1 + \varphi_2 \wedge \tau$ . Then  $d\varphi$  is vertical. We claim that for generic  $\varphi_1$ , one has  $d\varphi \neq 0$ . Indeed, suppose that  $d\varphi = 0$ . Then there exists  $\beta \in \Omega_c^{k-1}(N)$  such that  $\varphi = d\beta$ . Thus  $\varphi_1 = (d\beta)_1$ . Let  $S \subset N$  be a complete horizontal submanifold of dimension  $m - 1$  (eg the boundary at infinity of an isometric copy of  $\mathbb{H}_{\mathbb{R}}^m$  in  $\mathbb{H}_{\mathbb{C}}^m$ ). Since  $S$  is horizontal, by Stokes' theorem

$$\int_S \varphi_1 = \int_S (d\beta)_1 = \int_S d\beta = 0.$$

The claim follows. □

We can now conclude:

**End of proof of Theorem 6.1** Note that we can use Poincaré duality (Proposition 1.1(2)), since we know at this stage that the cohomology spaces we consider are Hausdorff. The vanishing results in items (2) and (3) follow from Lemma 6.3 and Poincaré duality. The nonvanishing ones are a consequence of Lemma 6.5 and Poincaré duality. □

## 6.2 Complement (on density) to Theorem 6.1

We establish two results (Propositions 6.7 and 6.11) that complement Theorem 6.1 and that could be useful in the future. The first one will serve partially in Section 7 to study the cohomology of  $SL_3(\mathbb{R})/SO_3(\mathbb{R})$ . The objects and notation are the same as in the previous section.

Recall from Theorem 6.1, that for  $k \in \{1, \dots, m\}$  and  $2m/k < p < 2m/(k - 1)$ , the space  $L^p H_{dR}^k(R)$  is Hausdorff, nonzero, and admits the subspace  $\{[d(\chi \cdot \pi^* \theta)] : \theta \in \Omega_c^{k-1}(N)\}$  as a dense subset. The first result of the section describes the classes  $[d(\chi \cdot \pi^* \theta)]$  that are null in  $L^p H_{dR}^k(R)$ :

**Proposition 6.7** *Let  $k \in \{1, \dots, m\}$  and  $2m/k < p < 2m/(k - 1)$ . For every  $\theta \in \Omega_c^{k-1}(N)$ , we have:*

- (1) *When  $k < m$ , the class  $[d(\chi \cdot \pi^* \theta)]$  is null in  $L^p H_{dR}^k(R)$  if and only if  $(d\theta)_1 = \gamma \wedge d\tau$  for some horizontal form  $\gamma \in \Omega_c^{k-2}(N)$ .*
- (2) *When  $k = m$ , the class  $[d(\chi \cdot \pi^* \theta)]$  is null in  $L^p H_{dR}^k(R)$  if and only if*

$$d(\theta - (-1)^m \mathcal{L}((d\theta)_1) \wedge \tau) = 0,$$

where  $\mathcal{L}: \Omega_1^m \rightarrow \Omega_1^{m-2}$  denotes the pointwise operator induced by the inverse of the Lefschetz isomorphism  $L_{m-2}: \wedge^{m-2} \mathfrak{n}_1^* \rightarrow \wedge^m \mathfrak{n}_1^*$ .

**Proof** (1) Let  $\theta \in \Omega_c^{k-1}(N)$ , and suppose that  $d\theta$  can be written  $d\theta = \gamma \wedge d\tau + \delta \wedge \tau$ , with  $\gamma$  and  $\delta$  horizontal. When  $k = 1$ , such a relation is impossible unless  $\theta = 0$ . Namely, the differential of a nonzero compactly supported function always has a nonzero horizontal component. Let us assume  $k \geq 2$ . We claim that there exists a horizontal form  $\beta \in \Omega_c^{k-2}(N)$  such that  $d\theta = d(\beta \wedge \tau)$ . In combination with Corollary 2.6 and Lemma 6.3, this yields  $[d(\chi \cdot \pi^* \theta)] = 0$ .

Since  $\beta$ ,  $\gamma$  and  $\delta$  are horizontal forms, the equation  $d\theta = d(\beta \wedge \tau)$  is equivalent to the system of two equations

$$\gamma \wedge d\tau = (-1)^k \beta \wedge d\tau \quad \text{and} \quad \delta \wedge \tau = d\beta \wedge \tau.$$

Set  $\beta := (-1)^k \gamma$ . Then the first equation is satisfied. Moreover, one has  $d\beta \wedge \tau = (-1)^k d\gamma \wedge \tau = (-1)^k (d\gamma)_1 \wedge \tau$ . Thus the second equation is satisfied if the relation  $\delta = (-1)^k (d\gamma)_1$  holds. Since  $dd\theta = 0$ , one has  $d\gamma \wedge d\tau + d\delta \wedge \tau - (-1)^k \delta \wedge d\tau = 0$ . This implies that  $((d\gamma)_1 - (-1)^k \delta) \wedge d\tau = 0$ , which in turn implies that  $(d\gamma)_1 - (-1)^k \delta = 0$  since the Lefschetz map  $L_{k-1}$  is injective (recall that  $k < m$  by assumption). Therefore the second equation is satisfied and the claim is proved.

Conversely, let  $\theta \in \Omega_c^{k-1}(N)$  be such that  $[d(\chi \cdot \pi^*\theta)] = 0$ . Denote by  $(q, \ell)$  the Poincaré dual of  $(p, k)$  relative to  $R$ . One has  $2m/(\ell + 1) < q < 2m/\ell$  and  $\ell > m$ . In particular  $L_{\ell-2}$  is not injective, and therefore the following subspace is nontrivial:

$$\Gamma = \{\alpha \in \Omega_c^{\ell-2}(N) : \alpha \text{ is horizontal and } \alpha \wedge d\tau = 0\}.$$

Pick  $\alpha \in \Gamma$  and consider the form  $\varphi = \alpha \wedge \tau \in \Omega_c^{\ell-1}(N)$ . One has  $d\varphi = d\alpha \wedge \tau + (-1)^\ell \alpha \wedge d\tau = d\alpha \wedge \tau$ . Thus  $d\varphi$  is vertical, and so by Lemma 6.5(2) the form  $\pi^*(d\varphi)$  belongs to  $\mathfrak{X}^{q,\ell}(R, \xi)$ . Our assumption  $[d(\chi \cdot \pi^*\theta)] = 0$ , in combination with Theorem 3.2(4), implies that  $\int_N d\varphi \wedge \theta = 0$ . With Stokes' formula and the definition of  $\varphi$ , it follows that  $\int_N \alpha \wedge \tau \wedge d\theta = 0$ , ie  $\int_N \alpha \wedge \tau \wedge (d\theta)_1 = 0$ . So far we have established that every  $\theta \in \Omega_c^{k-1}(N)$  such that  $[d(\chi \cdot \pi^*\theta)] = 0$  satisfies the property

$$(6.8) \quad \int_N \alpha \wedge \tau \wedge (d\theta)_1 = 0 \quad \text{for all } \alpha \in \Gamma.$$

When  $k \geq 2$ , we will show that property (6.8) implies that  $(d\theta)_1$  can be written  $\gamma \wedge d\tau$ . When  $k = 1$ , we will prove that (6.8) implies  $(d\theta)_1 = 0$ .

Suppose first that  $k = 1$ . One has  $\ell = 2m - 1$ ,  $L_{\ell-2} = 0$  and  $\Gamma = \Omega_1^{\ell-2} \cap \Omega_c^{\ell-2}(N)$ . Thus, property (6.8) yields that  $\int_N \omega \wedge \tau \wedge (d\theta)_1 = 0$  for every  $\omega \in \Omega_c^{\ell-2}(N)$ . This in turn implies that  $\tau \wedge (d\theta)_1 = 0$ , ie  $(d\theta)_1 = 0$ .

Suppose now that  $k \geq 2$ . We will use the following lemma:

**Lemma 6.9** *Let  $b: \wedge^{\ell-2} \mathfrak{n}_1^* \times \wedge^k \mathfrak{n}_1^* \rightarrow \mathbb{R}$ , be the nondegenerate bilinear form defined by  $b(u, v) = u \wedge v$ . Relative to  $b$ , one has  $(\text{Ker } L_{\ell-2})^\perp = \text{Im } L_{k-2}$ .*

**Proof** Since  $b$  is nondegenerate, the statement is equivalent to  $(\text{Im } L_{k-2})^\perp = \text{Ker } L_{\ell-2}$ . Let  $u \in \wedge^{\ell-2} \mathfrak{n}_1^*$ . It belongs to  $(\text{Im } L_{k-2})^\perp$  if and only if  $u \wedge v \wedge d\tau = 0$  for all  $v \in \wedge^{k-2} \mathfrak{n}_1^*$ . This is equivalent to  $u \wedge d\tau = 0$ , ie to  $u \in \text{Ker } L_{\ell-2}$ .  $\square$

Lemma 6.9 allows one to complete the proof of item (1) as follows. By definition,  $\Gamma$  is the space of compactly supported smooth sections of the left-invariant vector bundle over  $N$  generated by  $\text{Ker } L_{\ell-2}$ . Property (6.8) can be interpreted as saying that  $(d\theta)_1$  is a smooth section of the left-invariant vector bundle generated by  $(\text{Ker } L_{\ell-2})^\perp$ . By Lemma 6.9, this is equivalent to  $(d\theta)_1 = \gamma \wedge d\tau$  for some horizontal form  $\gamma \in \Omega_c^{k-2}(N)$ .

(2) Suppose that  $k = m$ , and let  $(q, m)$  be the Poincaré dual of  $(p, m)$  relative to  $R$ . One has  $2m/(m+1) < q < 2m/m = 2$ . Let  $\theta \in \Omega_c^{m-1}(N)$ . According to Theorem 3.2 and Poincaré duality (Proposition 1.1), the class  $[d(\chi \cdot \pi^*\theta)]$  vanishes in  $L^p \mathbb{H}_{\text{dR}}^m(R)$  if and only if  $T(\theta) = 0$  for all  $T \in \mathcal{D}^m(N)$  such that  $\pi^*T \in \mathfrak{X}^{q,m}(R, \xi)$ .

Since  $L_{m-2}$  is an isomorphism, there exist unique horizontal forms  $\alpha \in \Omega_c^{m-2}(N)$  and  $\beta \in \Omega_c^{m-1}(N)$  such that  $d\theta$  weight-decomposes as  $d\theta = \alpha \wedge d\tau + \beta \wedge \tau$ .

Let  $T \in \mathcal{D}^m(N)$  be such that  $\pi^*T \in \mathcal{X}^{q,m}(R, \xi)$ . Since  $N$  is contractible and  $T$  is closed, it admits a primitive, say  $S \in \mathcal{D}^{m-1}(N)$ . Then  $T(\theta)$  admits the following expression:

**Lemma 6.10** *With the notation above, one has*

$$T(\theta) = (-1)^m S_1((\beta - (-1)^m d\alpha) \wedge \tau).$$

Moreover,

$$(\beta - (-1)^m d\alpha) \wedge \tau = d(\theta - (-1)^m \mathcal{L}((d\theta)_1) \wedge \tau).$$

Assume for a moment that the lemma holds. Then the “if” part of item (2) follows immediately. To establish the “only if” part, we apply the lemma with some explicit currents  $T$ . Let  $\varphi_1 \in \Omega_c^{m-1}(N)$  be an arbitrary horizontal form, let  $\varphi_2 \in \Omega_c^{m-2}(N)$  be the horizontal form uniquely determined by the equation  $(d\varphi_1)_1 = -(-1)^m \varphi_2 \wedge d\tau$ . Set  $\varphi := \varphi_1 + \varphi_2 \wedge \tau$ . Then an easy computation shows that  $d\varphi$  is vertical. Thus, by Lemma 6.5(2), the current  $\pi^*(d\varphi)$  belongs to  $\mathcal{X}^{q,m}(R, \xi)$ . Lemma 6.10 applied to  $T = d\varphi$  yields that

$$\int_N \varphi_1 \wedge (\beta - (-1)^m d\alpha) \wedge \tau = 0$$

for every horizontal  $\varphi_1 \in \Omega_c^{m-1}(N)$ . Therefore  $(\beta - (-1)^m d\alpha) \wedge \tau = 0$ , and the second part of the lemma completes the proof of item (2).  $\square$

**Proof of Lemma 6.10** Since  $S$  is a primitive of  $T$ , we have  $T(\theta) = dS(\theta) = (-1)^m S(d\theta)$ . From relation (6.4) and the expression  $d\theta = \alpha \wedge d\tau + \beta \wedge \tau$ , it follows that  $S(d\theta) = S_1(\beta \wedge \tau) + S_2(\tau \wedge \alpha \wedge d\tau)$ . By Lemma 6.5(1) the current  $T$  is vertical. Thus (by a simple computation)  $(dS_1)_1 = -(-1)^m S_2 \wedge d\tau$ . Therefore,

$$\begin{aligned} S_2(\tau \wedge \alpha \wedge d\tau) &= (-1)^m S_2(d\tau \wedge \alpha \wedge \tau) = -(dS_1)_1(\alpha \wedge \tau) \\ &= -dS_1(\alpha \wedge \tau) = -(-1)^m S_1(d(\alpha \wedge \tau)) \\ &= S_1(-(-1)^m d\alpha \wedge \tau). \end{aligned}$$

The expected formula for  $T(\theta)$  follows. To establish the second formula, we compute

$$\begin{aligned} d(\theta - (-1)^m \mathcal{L}((d\theta)_1) \wedge \tau) &= d(\theta - (-1)^m \alpha \wedge \tau) \\ &= \alpha \wedge d\tau + \beta \wedge \tau - (-1)^m d\alpha \wedge \tau - \alpha \wedge d\tau \\ &= (\beta - (-1)^m d\alpha) \wedge \tau. \end{aligned} \quad \square$$

The second result of the section deals with the Banach space  $\mathcal{X}^{p,k}(R, \xi)$  for  $k \in \{m, \dots, 2m-1\}$  and  $2m/(k+1) < p < 2m/k$ . According to Lemma 6.5(2), the forms  $\pi^*(d\varphi)$ , where  $\varphi \in \Omega_c^{k-1}(N)$  and  $d\varphi$  is vertical, belong to  $\mathcal{X}^{p,k}(R, \xi)$ . A natural problem is to determine whether they form a dense subspace. For the norm topology, we do not know, but for the current topology this is indeed the case:

**Proposition 6.11** *Let  $k \in \{m, \dots, 2m - 1\}$  and  $2m/(k + 1) < p < 2m/k$ . The set*

$$\{d\varphi : \varphi \in \Omega_c^{k-1}(N), d\varphi \text{ is vertical}\}$$

*is a dense subspace in the sense of currents in  $\{T \in \mathcal{D}'^k(N) : \pi^*T \in \mathcal{L}^{p,k}(R, \xi)\}$ .*

**Proof** Set  $F := \{d\varphi : \varphi \in \Omega_c^{k-1}(N), d\varphi \text{ is vertical}\}$  and  $E := \{T \in \mathcal{D}'^k(N) : \pi^*T \in \mathcal{L}^{p,k}(R, \xi)\}$  for simplicity. Let  $(q, \ell)$  be the Poincaré dual of  $(p, k)$  relative to  $R$ . The topology on  $E$ , which is induced by the weak\*-topology of  $\mathcal{D}'^k(N)$ , is generated by the linear forms  $\Lambda_\theta : E \rightarrow \mathbb{R}$  defined by  $\Lambda_\theta(T) = T(\theta)$ , where  $\theta$  belongs to  $\Omega_c^{\ell-1}(N)$ . We shall let  $E_{\text{top}}$  denote  $E$  equipped with this topology.

According to the Hahn–Banach theorem, showing that  $F$  is dense in  $E_{\text{top}}$  is equivalent to proving the triviality of every  $\Lambda \in E_{\text{top}}^*$  such that  $\Lambda(F) = \{0\}$ .

Since every element of  $E_{\text{top}}^*$  is a  $\Lambda_\theta$  for some  $\theta \in \Omega_c^{\ell-1}(N)$  (see [Rudin 1973, Theorem 3.10]), we are led to showing the following: if  $\theta \in \Omega_c^{\ell-1}(N)$  satisfies  $\int_N d\varphi \wedge \theta = 0$  for every  $d\varphi \in F$ , then  $\Lambda_\theta = 0$ .

By analyzing the proof of the previous Proposition 6.7, one sees that the forms  $\theta$  such that  $\int_N d\varphi \wedge \theta = 0$  for every  $d\varphi \in F$  are precisely those for which  $[d(\chi \cdot \pi^*\theta)] = 0$  in  $L^q\text{H}_{\text{dR}}^\ell(R)$ . Therefore they satisfy  $\Lambda_\theta = 0$ , thanks to Theorem 3.2(4).

To finish, let us explain briefly how to deduce from the proof of the previous proposition, that the above forms  $\theta$  satisfy  $[d(\chi \cdot \pi^*\theta)] = 0$ . In the case  $\ell < m$ , we consider, as in the “only if” part of item (1), the forms  $d\varphi$  with  $\varphi = \alpha \wedge \tau$ ; we obtain that  $(d\theta)_1 = \gamma \wedge \tau$ . Then the “if” part of item (1) implies that  $[d(\chi \cdot \pi^*\theta)] = 0$ . In the case  $\ell = m$ , as in the proof of item (2), we consider the forms  $\varphi$  and the currents  $T = d\varphi$ , and we conclude by the same line of argument. □

## 7 The symmetric space $\text{SL}_3(\mathbb{R})/\text{SO}_3(\mathbb{R})$

We prove Theorem D, stated in the introduction, which describes the second  $L^p$ -cohomology of  $\text{SL}_3(\mathbb{R})/\text{SO}_3(\mathbb{R})$ . The strategy is similar to the one used in Section 5 to study the second  $L^p$ -cohomology of the groups  $S_\alpha$ . It strongly relies on the description of the cohomology of the complex hyperbolic plane discussed in Section 6.

### 7.1 Notation and decomposition of $\text{SL}_3(\mathbb{R})$

At first we introduce the various subgroups of  $\text{SL}_3(\mathbb{R})$  that we will be working with in the sequel.

The relevant Iwasawa decomposition here is  $\text{SL}_3(\mathbb{R}) = KAN$ , with  $K = \text{SO}_3(\mathbb{R})$ ,  $A = \text{Diag}(\mathbb{R}^3) \cap \text{SL}_3(\mathbb{R})$  and

$$N = \left\{ \begin{pmatrix} 1 & x & z \\ 0 & 1 & y \\ 0 & 0 & 1 \end{pmatrix} : x, y, z \in \mathbb{R} \right\} \simeq \text{Heis}(3).$$

Let  $\mathfrak{a}$  and  $\mathfrak{n}$  be the Lie algebras of  $A$  and  $N$ , respectively. Every element of  $\mathfrak{n}$  can be naturally denoted by a triple  $(x, y, z) \in \mathbb{R}^3$ .

Let  $\xi, \eta \in \mathfrak{a}$  be defined by  $\xi = \text{diag}(-1, 0, 1)$  and  $\eta = \frac{1}{3} \text{diag}(1, -2, 1)$ . They act on  $\mathfrak{n}$  by

$$(7.1) \quad \text{ad}\xi \cdot (x, y, z) = (-x, -y, -2z) \quad \text{and} \quad \text{ad}\eta \cdot (x, y, z) = (x, -y, 0).$$

We consider the following subgroups of  $\text{SL}_3(\mathbb{R})$ :

$$R := \{e^{t\xi}\}_{t \in \mathbb{R}} \times N \simeq \mathbb{H}_{\mathbb{C}}^2, \quad H := \{e^{s\eta}\}_{s \in \mathbb{R}} \times N \quad \text{and} \quad S := A \times N = \{e^{s\eta}\}_{s \in \mathbb{R}} \times R = \{e^{t\xi}\}_{t \in \mathbb{R}} \times H.$$

The Lie group  $S$  is isometric to the symmetric space  $\text{SL}_3(\mathbb{R})/\text{SO}_3(\mathbb{R})$ .

### 7.2 First observations

We derive from previous results some preliminary observations on  $L^p H_{\text{dR}}^2(S)$ . The notation is the same as in the previous section.

**Proposition 7.2** For  $p < \frac{4}{3}$ , we have  $L^p H_{\text{dR}}^2(S) = \{0\}$ .

**Proof** Let  $\mathfrak{h}$  denotes the Lie algebra of  $H$ . Set  $\delta := \text{ad}\xi|_{\mathfrak{h}} \in \text{Der}(\mathfrak{h})$ , so that  $S$  can be written  $S = \mathbb{R} \times_{\delta} H$ . The ordered list of eigenvalues of  $-\delta$ , enumerated with multiplicity, is

$$\lambda_1 = 0 < \lambda_2 = \lambda_3 = 1 < \lambda_4 = 2.$$

Thus, with the notation of Section 3, the trace of  $-\delta$  is  $h = 4$ , and one has  $W_2 = \lambda_3 + \lambda_4 = 3$ . Therefore the statement follows from Theorem 3.2(1). □

**Proposition 7.3** For  $p \in (\frac{4}{3}; 4) \setminus \{2\}$ , the space  $L^p H_{\text{dR}}^2(R)$  is nonzero and Hausdorff, and there exists a linear isomorphism

$$L^p H_{\text{dR}}^2(S) \simeq \left\{ [\omega] \in L^p H_{\text{dR}}^2(R) : \int_{\mathbb{R}} \|e^{s\text{ad}\eta^*}[\omega]\|_{L^p H^2(R)}^p ds < +\infty \right\}.$$

**Proof** When  $p \in (\frac{4}{3}; 4) \setminus \{2\}$ , Theorem 6.1 shows that  $L^p H_{\text{dR}}^2(R)$  is nonzero and Hausdorff, and that  $L^p H_{\text{dR}}^k(R) = \{0\}$  in all degrees  $k \neq 2$ . Since  $S = \{e^{s\eta}\}_{s \in \mathbb{R}} \times R$ , the above description of the cohomology of  $R$ , in combination with a Hochschild–Serre spectral sequence argument [Bourdon and Rémy 2023, Corollary 6.10], yields the desired linear isomorphism. □

**Proposition 7.4** For  $p > 4$ , the space  $\overline{L^p H_{\text{dR}}^2(S)}$  is nonzero.

**Proof** Consider again  $\lambda_1 = 0 < \lambda_2 = \lambda_3 = 1 < \lambda_4 = 2$ , the list of the eigenvalues of  $-\delta = -\text{ad}\xi|_{\mathfrak{h}} \in \text{Der}(\mathfrak{h})$ . The trace of  $-\delta$  is  $h = 4$ , and one has  $w_2 = \lambda_1 + \lambda_2 = 1$ . Since the rank of  $S$  is equal to 2, it follows from [Bourdon and Rémy 2023, Theorem C and Corollary 3.4] that  $\overline{L^p H_{\text{dR}}^2(S)}$  is nonzero for  $p > h/w_2 = 4$ . □

### 7.3 Auxiliary results on $\mathbb{H}_{\mathbb{C}}^2$

This section is devoted to auxiliary results (Lemmas 7.5 and 7.6) that will serve in the next section to prove Theorem D.

Recall that  $R = \{e^{t\xi}\}_{t \in \mathbb{R}} \times N \simeq \mathbb{H}_{\mathbb{C}}^2$ . Let  $\pi_N$  be the projection map from  $R$  onto  $N$ .

**Lemma 7.5** *Suppose that  $p \in (2; 4)$ , and let  $\theta \in \Omega_c^1(N) \setminus \{0\}$  be of the form  $\theta = f dx$  or  $g dy$ . Then:*

- (1) *The class  $[d(\chi \cdot \pi_N^* \theta)]$  is nonzero in  $L^p H_{\text{dR}}^2(R)$ .*
- (2) *If  $\theta = f dx$  (resp.  $g dy$ ), one has*

$$\| [d(\chi \cdot \pi_N^* e^{s \text{ad} \eta^*} \theta)] \|_{L^p H^2(R)} \rightarrow 0$$

*exponentially fast, when  $s$  tends to  $-\infty$  (resp.  $+\infty$ ).*

**Proof** (1) We apply the criterion in Proposition 6.7(2). Suppose first that  $\theta = f dx$ . With the notation of Sections 6.1 and 6.2, one has  $d\theta = (Y \cdot f) dy \wedge dx + (Z \cdot f) \tau \wedge dx$ . Since  $d\tau = -dx \wedge dy$ , we get that

$$d(\theta - \mathcal{L}((d\theta)_1)\tau) = d(\theta - (Y \cdot f)\tau) = -(Z \cdot f + X \cdot Y \cdot f) dx \wedge \tau - (Y^2 \cdot f) dy \wedge \tau.$$

The term  $Y^2 \cdot f$  is nonzero since the function  $f$  is nonzero and has compact support. Therefore  $d(\theta - \mathcal{L}((d\theta)_1)\tau)$  is nonzero, and the statement follows from Proposition 6.7(2). The case  $\theta = g dy$  is similar.

(2) Suppose that  $\theta = f dx$ . For  $(s, t) \in \mathbb{R}^2$ , one has

$$e^{t \text{ad} \xi^*} (e^{s \text{ad} \eta^*} \theta) = (e^{t \text{ad} \xi + s \text{ad} \eta})^* \theta \quad \text{and} \quad e^{t \text{ad} \xi^*} (d e^{s \text{ad} \eta^*} \theta) = (e^{t \text{ad} \xi + s \text{ad} \eta})^* d\theta.$$

By Lemma 3.6 and relation (7.1), their  $L^p$ -norms satisfy

$$\begin{aligned} \| (e^{t \text{ad} \xi + s \text{ad} \eta})^* \theta \|_{L^p \Omega^1(N)} &\asymp e^{(4/p-1)t+s} \| f \|_p, \\ \| (e^{t \text{ad} \xi + s \text{ad} \eta})^* d\theta \|_{L^p \Omega^2(N)} &\asymp e^{-(2-4/p)t} \| Y \cdot f \|_p + e^{-(3-4/p)t+s} \| Z \cdot f \|_p. \end{aligned}$$

Set  $a = 4/p - 1$ ,  $b = 2 - 4/p$  and  $c = 3 - 4/p$ . One has  $a, b, c > 0$  since  $2 < p < 4$ . From Proposition 3.4, it follows that

$$\| [d(\chi \cdot \pi_N^* e^{s \text{ad} \eta^*} \theta)] \|_{L^p H^2(R)} \leq C \inf_{t \in \mathbb{R}} \{ (e^{at} + e^{-ct})e^s + e^{-bt} \}.$$

Suppose that  $s \rightarrow -\infty$ , and set  $t = -s/2a$ . Then

$$(e^{at} + e^{-ct})e^s + e^{-bt} = e^{s/2} + e^{((c/2a)+1)s} + e^{(b/2a)s},$$

which tends to 0 exponentially fast. The case  $\theta = g dy$  is similar. □

**Lemma 7.6** *Suppose that  $p \in (2; 4)$ . There exist nonzero forms  $\theta = f dx$  and  $\Theta = g dy$  in  $\Omega_c^1(N)$  such that  $[d(\chi \cdot \pi_N^* \theta)] = [d(\chi \cdot \pi_N^* \Theta)]$  in  $L^p H_{\text{dR}}^2(R)$ .*

**Proof** Let  $u$  be an arbitrary nonzero function in  $\Omega_c^0(N)$ . Its differential is  $(X \cdot u) dx + (Y \cdot u) dy + (Z \cdot u)\tau$ . Set  $f := X \cdot u$ ,  $g := -Y \cdot u$  and  $h := -Z \cdot u$ , and let  $\theta = f dx$  and  $\Theta = g dy$ . By Proposition 6.7(2), one has  $[d(\chi \cdot \pi_N^* \theta)] = [d(\chi \cdot \pi_N^* \Theta)]$  in  $L^p H_{dR}^2(R)$ . Indeed,

$$d(\theta - \Theta) = d(h\tau) = dh \wedge \tau + h d\tau,$$

thus  $\mathcal{L}((\theta - \Theta)_1) = h$ , and we get that  $d(\theta - \Theta - \mathcal{L}((\theta - \Theta)_1)\tau) = 0$ . □

### 7.4 Proof of Theorem D

Thanks to Propositions 7.2 and 7.4, we can restrict ourselves to the region  $p \in (\frac{4}{3}; 4) \setminus \{2\}$ . In this region, Proposition 7.3 shows that there is a linear isomorphism

$$(7.7) \quad L^p H_{dR}^2(S) \simeq \left\{ [\omega] \in L^p H_{dR}^2(R) : \int_{\mathbb{R}} \|e^{s \text{ad}\eta^*}[\omega]\|_{L^p H^2(R)}^p ds < \infty \right\}.$$

We will use this representation to prove the theorem.

**Step 1**  $L^p H_{dR}^2(S) = \{0\}$  when  $p \in (\frac{4}{3}; 2)$ .

Let  $p \in (\frac{4}{3}, 2)$  and let  $(q, 2)$  be the Poincaré dual of  $(p, 2)$  relative to  $R$ . One has  $q \in (2; 4)$ . According to the relation (7.7), it is enough to show that for every nontrivial  $[\omega]$ , one has  $\|e^{s \text{ad}\eta^*}[\omega]\|_{L^p H^2(R)} \rightarrow +\infty$  when  $s$  tends to  $+\infty$  or to  $-\infty$ .

So let  $[\omega]$  be a nontrivial class in  $L^p H_{dR}^2(R)$ . By Theorem 3.2(4), it admits a boundary value  $T$  in  $\mathcal{D}'^2(N) \cap \text{Ker } d$ , so that

$$\|[\omega]\|_{L^p H^2(R)} = \sup\{T(\theta) : \theta \in \Omega_c^1(N), \|[d(\chi \cdot \pi_N^* \theta)]\|_{L^q H^2(R)} \leq 1\}.$$

In the group  $R$ , right multiplication by  $\exp t\xi$  commutes with conjugacy by  $\exp s\eta$ . Therefore the boundary value of the class  $e^{s \text{ad}\eta^*}[\omega]$  is the current  $e^{s \text{ad}\eta^*}T$ . With a change of variable, one gets

$$\|e^{s \text{ad}\eta^*}[\omega]\|_{L^p H^2(R)} = \sup\{T(\theta) : \theta \in \Omega_c^1(N), \text{ with } \|[d(\chi \cdot \pi_N^* e^{s \text{ad}\eta^*} \theta)]\|_{L^q H^2(R)} \leq 1\}.$$

By Lemma 6.5, the current  $T$  is vertical, thus it can be written as  $T = F dy \wedge \tau + G dx \wedge \tau$ , with  $F, G \in \mathcal{D}'^0(N)$ . If  $F \neq 0$  (resp.  $G \neq 0$ ), then for  $\theta = f dx \in \Omega_c^1(N)$  (resp.  $\theta = g dy$ ), one has  $T(\theta) = F(f \text{ vol})$  (resp.  $-G(g \text{ vol})$ ). In any case, there exists  $\theta \in \Omega_c^1(N)$ , of the form  $f dx$  or  $g dy$ , such that  $T(\theta) = 1$ . The above equality, in combination with Lemma 7.5(2), yields that

$$\|e^{s \text{ad}\eta^*}[\omega]\|_{L^p H^2(R)} \geq \|[d(\chi \cdot \pi_N^* e^{s \text{ad}\eta^*} \theta)]\|_{L^q H^2(R)}^{-1} \rightarrow +\infty$$

when  $s$  tends to  $+\infty$  or to  $-\infty$ .

**Step 2**  $L^p H_{dR}^2(S) \neq \{0\}$  when  $p \in (2; 4)$ .

Let  $p \in (2; 4)$ . We will exhibit a nontrivial element in the right-hand side of (7.7).

Let  $\theta = f dx$  and  $\Theta = g dy$  be as in Lemma 7.6. Set  $\omega := d(\chi \cdot \pi_N^* \theta)$  and  $\Omega := d(\chi \cdot \pi_N^* \Theta)$ . By Lemmas 7.6 and 7.5(1), their classes  $[\omega]$  and  $[\Omega]$  are equal and nonzero in  $L^p H_{\text{dR}}^2(R)$ .

Since  $\xi$  and  $\eta$  commute,  $e^{s \text{ad} \eta^*} \omega = d(\chi \cdot \pi_N^* e^{s \text{ad} \eta^*} \theta)$ . So by Lemma 7.5(2), the norm  $\|e^{s \text{ad} \eta^*} [\omega]\|_{L^p H^2(R)}$  tends to 0 exponentially fast when  $s$  tends to  $-\infty$ , similarly for  $\|e^{s \text{ad} \eta^*} [\Omega]\|_{L^p H^2(S)}$  when  $s$  tends to  $+\infty$ . Since  $[\omega] = [\Omega]$ , the integral  $\int_{\mathbb{R}} \|e^{s \text{ad} \eta^*} [\omega]\|_{L^p H^2(R)}^p ds$  converges. Thus  $[\omega]$  provides a nontrivial element in the right-hand side of (7.7).

## Appendix The groups $S_\alpha \in \mathcal{G}^{r,n}$ : basic properties

Let  $r, n \in \mathbb{N}$ . We consider here the solvable Lie groups of the form  $S_\alpha = \mathbb{R}^r \rtimes_\alpha \mathbb{R}^n$  for a Lie group morphism  $\alpha: \mathbb{R}^r \rightarrow \{\text{diagonal automorphisms of } \mathbb{R}^n\}$ . Let  $\varpi_i \in (\mathbb{R}^r)^*$  for  $i = 1, \dots, n$  denote the *weights* associated to  $\alpha$ , ie the linear forms such that  $\alpha = e^{\text{diag}(\varpi_1, \dots, \varpi_n)}$ .

Some groups  $S_\alpha$  can be written with several pairs of exponents  $r, n$  (for instance when they are abelian). In the sequel we will always assume that the dimension  $n$  of the second factor is minimal and nonzero. This assumption is equivalent to requiring every weight  $\varpi_i$  to be nonzero; and it forces the rank of  $S_\alpha$  to be equal to  $r$ .

Let  $\mathcal{G}^{r,n}$  denote the set of the groups  $S_\alpha$  of exponents  $r, n$  (with the above convention).

We remark that the groups  $S_\alpha$  appear as special cases of the so-called *abelian-by-abelian* solvable Lie groups. The latter groups were considered by Peng [2011a; 2011b]. For such groups which are, in addition, unimodular, she established several quasi-isometric rigidity results.

This section is devoted to the following proposition, which establishes some of the basic properties of  $S_\alpha$ . The first two are elementary. The third one follows from Azencott and Wilson's classification [1976] of Lie groups of nonpositive curvature; see also [Heber 1993] for a detailed account of their geometric properties.

**Proposition A.1** *Let  $S_\alpha \in \mathcal{G}^{r,n}$ . Then:*

- (1)  $S_\alpha$  admits **no** nontrivial abelian direct factor if, and only if, the weights  $\varpi_1, \dots, \varpi_n$  generate the vector space  $(\mathbb{R}^r)^*$ .
- (2) Suppose that  $S_\alpha$  has no abelian direct factor. Then  $S_\alpha$  is reducible — ie splits as a direct product of nontrivial closed subgroups — if and only if there exists a nontrivial partition  $I_1 \sqcup I_2 = \{1, \dots, n\}$  such that

$$\text{Span}\{\varpi_i : i \in I_1\} \cap \text{Span}\{\varpi_i : i \in I_2\} = \{0\}.$$

- (3)  $S_\alpha$  admits a left-invariant Riemannian metric of nonpositive curvature if, and only if, 0 does **not** belong to the convex hull of  $\{\varpi_1, \dots, \varpi_n\}$  in  $(\mathbb{R}^r)^*$ . In this case the factor  $\mathbb{R}^r$  is a totally geodesic Euclidean subspace of maximal dimension in  $S_\alpha$ .

- (4) There exists  $\xi \in \mathbb{R}^r$  such that the associated subgroup  $(\mathbb{R}\xi) \times \mathbb{R}^n$  is quasi-isometric to the real hyperbolic space  $\mathbb{H}_{\mathbb{R}}^{n+1}$  if, and only if, the weights  $\varpi_1, \dots, \varpi_n$  are contained in an affine subspace of  $(\mathbb{R}^r)^*$ , disjoint from 0.

**Remark A.2** It follows from item (2) above that the groups  $S_\alpha$  which are irreducible, of higher rank, and of smallest dimension, belong to the family  $\mathcal{G}^{2,3}$ .

**Remark A.3** When  $\alpha$  is injective, ie when  $S_\alpha$  has no nontrivial abelian direct factor (see item (1) above), the group  $S_\alpha$  is isomorphic to the (upper-triangular) real matrix group

$$\left\{ \left( \begin{array}{cccc|c} e^{\varpi_1(u)} & 0 & \dots & 0 & x_1 \\ & \ddots & \ddots & \vdots & \vdots \\ & & e^{\varpi_{n-1}(u)} & 0 & x_{n-1} \\ & & & e^{\varpi_n(u)} & x_n \\ & & & & 1 \end{array} \right) : u \in \mathbb{R}^r, (x_1, \dots, x_n) \in \mathbb{R}^n \right\}.$$

These groups appear in [de Cornulier 2020], where the geometry of their asymptotic cones is discussed.

**Proof of Proposition A.1** We start with some notation and preliminaries. Set  $I := \{1, \dots, n\}$  and denote by  $(e_i)_{i \in I}$  the canonical basis of  $\mathbb{R}^n$ . The multiplication law of  $S_\alpha$  is

$$(u, x) \cdot (v, y) = (u + v, x + \alpha(u)y).$$

Let us denote the Lie algebra of  $S_\alpha$  by  $\mathfrak{s}_\alpha$ , and set  $\Pi := \text{diag}(\varpi_1, \dots, \varpi_n) \in (\mathbb{R}^r)^* \otimes \text{Diag}(\mathbb{R}^n)$ , so that  $\alpha = e^\Pi$ . A standard computation gives the following expression for the Lie bracket in  $\mathfrak{s}_\alpha$ :

(A.4) 
$$[(U, X), (V, Y)] = (0, \Pi(U)Y - \Pi(V)X).$$

Since every  $\varpi_i$  is nonzero, one checks that the center of  $\mathfrak{s}_\alpha$  is

$$\mathfrak{z}(\mathfrak{s}_\alpha) = \{(U, 0) \in \mathfrak{s}_\alpha : \varpi_i(U) = 0 \text{ for all } i\},$$

and its derived subalgebra is  $[\mathfrak{s}_\alpha, \mathfrak{s}_\alpha] = \{0_{\mathbb{R}^r}\} \times \mathbb{R}^n \simeq \mathbb{R}^n$ .

- (1) Suppose that the weights  $\varpi_1, \dots, \varpi_n$  do not generate  $(\mathbb{R}^r)^*$ . Then  $\text{Ker } \Pi = \bigcap_{i \in I} \text{Ker } \varpi_i$  is nontrivial. Write  $\mathbb{R}^r = \text{Ker } \Pi \oplus E$ , set  $\mathfrak{h} := \text{Ker } \Pi \times \{0_{\mathbb{R}^n}\}$  and  $\mathfrak{k} := E \times \mathbb{R}^n$ . Then  $\mathfrak{h}$  and  $\mathfrak{k}$  are supplementary subalgebras in  $\mathfrak{s}_\alpha$ ; moreover,  $\mathfrak{h}$  is central, thus  $S_\alpha$  admits a direct abelian factor.

Conversely, suppose that  $S_\alpha$  admits a direct abelian factor. Then the center of  $\mathfrak{s}_\alpha$  is nontrivial. By the above description of  $\mathfrak{z}(\mathfrak{s}_\alpha)$ , there exists a nonzero  $U \in \mathbb{R}^r$  that belongs to the kernel of every  $\varpi_i$ . Therefore the weights  $\varpi_i$  do not generate  $(\mathbb{R}^r)^*$ .

- (2) Let  $I = I_1 \sqcup I_2$  be a nontrivial partition as in the statement. One has

$$\bigcap_{i \in I_1} \text{Ker}(\varpi_i) + \bigcap_{i \in I_2} \text{Ker}(\varpi_i) = \mathbb{R}^r.$$

By assumption, every  $\varpi_i$  is nonzero. Therefore  $\mathbb{R}^r$  admits proper supplementary subspaces  $E_1, E_2$  such that for  $j = 1, 2$ ,

$$\{0\} \neq E_j \subset \bigcap_{i \in I \setminus I_j} \text{Ker}(\varpi_i).$$

Set  $\mathfrak{h}_j := E_j \times \text{Span}\{e_i : i \in I_j\}$ . Then  $\mathfrak{h}_1$  and  $\mathfrak{h}_2$  are supplementary subalgebras in  $\mathfrak{s}_\alpha$ . They satisfy  $[\mathfrak{h}_1, \mathfrak{h}_2] = 0$ ; indeed, for every  $U \in E_1$  and  $Y \in \text{Span}\{e_i ; i \in I_2\}$ , one has

$$\Pi(U)Y = \sum_{i \in I_2} Y_i \varpi_i(U) e_i = 0,$$

and similarly for  $V \in E_2$  and  $X \in \text{Span}\{e_i : i \in I_1\}$ . Thus  $S_\alpha$  is reducible.

Conversely, suppose that  $\mathfrak{s}_\alpha$  admits supplementary (nonabelian) subalgebras  $\mathfrak{h}_1, \mathfrak{h}_2$  such that  $[\mathfrak{h}_1, \mathfrak{h}_2] = 0$ . One has

$$[\mathfrak{h}_1, \mathfrak{h}_1] \cap [\mathfrak{h}_2, \mathfrak{h}_2] \subset \mathfrak{h}_1 \cap \mathfrak{h}_2 = \{0\} \quad \text{and} \quad [\mathfrak{s}_\alpha, \mathfrak{s}_\alpha] = [\mathfrak{h}_1 + \mathfrak{h}_2, \mathfrak{h}_1 + \mathfrak{h}_2] = [\mathfrak{h}_1, \mathfrak{h}_1] + [\mathfrak{h}_2, \mathfrak{h}_2].$$

Therefore  $[\mathfrak{s}_\alpha, \mathfrak{s}_\alpha] = [\mathfrak{h}_1, \mathfrak{h}_1] \oplus [\mathfrak{h}_2, \mathfrak{h}_2]$ , which in turn implies that

**(A.5)** 
$$\mathfrak{h}_j \cap [\mathfrak{s}_\alpha, \mathfrak{s}_\alpha] = [\mathfrak{h}_j, \mathfrak{h}_j]$$

for  $j = 1, 2$ . Let  $\sigma : \mathbb{R}^r \times \mathbb{R}^n \rightarrow \mathbb{R}^r$  be the projection map on the first factor, and set  $E_j := \sigma(\mathfrak{h}_j)$  for  $j = 1, 2$ . We claim that

**(A.6)** 
$$\mathfrak{h}_j = E_j \times [\mathfrak{h}_j, \mathfrak{h}_j].$$

To see this, let  $(U, X) \in \mathfrak{h}_j$ . One has  $U = \sigma(U, X)$ , thus  $U \in E_j$ . Since  $\mathfrak{h}_j$  is an ideal, relations (A.4) and (A.5) imply for every  $V \in \mathbb{R}^r$ ,

$$(0, -\Pi(V)X) = [(U, X), (V, 0)] \in \mathfrak{h}_j \cap [\mathfrak{s}_\alpha, \mathfrak{s}_\alpha] = [\mathfrak{h}_j, \mathfrak{h}_j].$$

By choosing  $V$  so that  $\Pi(V)$  is invertible, one has  $X \in \Pi(V)^{-1}[\mathfrak{h}_j, \mathfrak{h}_j]$ . On the other hand,  $\mathfrak{h}_j$  is an ideal, thus so is  $[\mathfrak{h}_j, \mathfrak{h}_j]$ . In combination with (A.4), this implies that  $\Pi(V)[\mathfrak{h}_j, \mathfrak{h}_j] = [\mathfrak{h}_j, \mathfrak{h}_j]$ . Therefore  $X \in [\mathfrak{h}_j, \mathfrak{h}_j]$ , and claim (A.6) now follows easily.

The subalgebras  $\mathfrak{h}_1$  and  $\mathfrak{h}_2$  are supplementary subspaces in  $\mathfrak{s}_\alpha$ ; thus so are  $E_1$  and  $E_2$  in  $\mathbb{R}^r$ , thanks to (A.6). Since  $\mathfrak{h}_j$  is nonabelian,  $E_j$  is nonzero. Set  $I_1 := \{i \in I : \varpi_i|_{E_2} = 0\}$  and  $I_2 := \{i \in I : \varpi_i|_{E_1} = 0\}$ . Observe that  $I_1 \cap I_2 = \emptyset$  since every  $\varpi_i$  is nonzero. We claim that  $I_1$  and  $I_2$  form a nontrivial partition of  $I$ . The proof of item (2) then follows easily. Let  $(U, X) \in \mathfrak{h}_1$  and  $(V, Y) \in \mathfrak{h}_2$ . Since  $[\mathfrak{h}_1, \mathfrak{h}_2] = 0$ , relation (A.4) implies that  $\Pi(U)Y = \Pi(V)X$ . By (A.6), one has  $X \in [\mathfrak{h}_1, \mathfrak{h}_1]$  and  $Y \in [\mathfrak{h}_2, \mathfrak{h}_2]$ . Moreover,  $[\mathfrak{h}_j, \mathfrak{h}_j]$  is an ideal, so it is invariant by  $\Pi(\mathbb{R}^r)$ . Therefore  $\Pi(U)Y$  and  $\Pi(V)X$  belong to  $[\mathfrak{h}_j, \mathfrak{h}_j]$  for  $j = 1, 2$ . Since the intersection of the latter subspaces is  $\{0\}$ , the vectors  $\Pi(U)Y$  and  $\Pi(V)X$  are 0. In other words, we have shown that

$$[\mathfrak{h}_1, \mathfrak{h}_1] \subset \bigcap_{V \in E_2} \text{Ker } \Pi(V) \quad \text{and} \quad [\mathfrak{h}_2, \mathfrak{h}_2] \subset \bigcap_{U \in E_1} \text{Ker } \Pi(U).$$

An easy computation shows that  $\bigcap_{V \in E_2} \text{Ker } \Pi(V) = \text{Span}\{e_i : i \in I_1\}$ , and similarly  $\bigcap_{U \in E_1} \text{Ker } \Pi(U) = \text{Span}\{e_i : i \in I_2\}$ . Since the subspaces  $[h_1, h_1]$  and  $[h_2, h_2]$  generate  $\mathbb{R}^n$ , we finally obtain that  $I_1 \cup I_2 = I$ .

(3) By [Azencott and Wilson 1976], a connected Lie group  $S$  admits a left-invariant nonpositively curved Riemannian metric if, and only if, its Lie algebra  $\mathfrak{s}$  is an *NC algebra*. This means that  $\mathfrak{s}$  enjoys the following properties:

- (i)  $\mathfrak{n} := [\mathfrak{s}, \mathfrak{s}]$  is a nilpotent ideal that is complemented in  $\mathfrak{s}$  by an abelian subalgebra  $\mathfrak{a}$ .
- (ii) There exists an element  $\xi \in \mathfrak{a}$  such that all the eigenvalues of  $\text{ad}\xi|_{\mathfrak{n}}$  have negative real parts.
- (iii) The action of  $\mathfrak{a}$  on  $\mathfrak{n}$  satisfies 3 additional conditions, which are automatically fulfilled when  $\mathfrak{n}$  is abelian and the  $\mathfrak{a}$ -action is semisimple with real eigenvalues.

We refer to [Azencott and Wilson 1976, Definition 6.2] for the precise definition of NC algebra, and to the paragraph right after it for a discussion of the special cases.

Clearly the Lie algebra  $\mathfrak{s}_\alpha$  satisfies items (i) and (iii). It satisfies (ii) if and only if there exists a  $U \in \mathbb{R}^r$  such that  $\varpi_i(U) \leq -1$  for all  $i \in I$ . Let  $v_i \in \mathbb{R}^r$  be such that  $\varpi_i = \langle \cdot, v_i \rangle$ , where  $\langle \cdot, \cdot \rangle$  is a scalar product. One has  $\varpi_i(U) \leq -1$  for every  $i \in I$  if, and only if, every  $v_i$  belongs to the subset defined by the inequality  $\langle U, \cdot \rangle \leq -1$ ; ie to the affine half-space of  $\mathbb{R}^r$ , disjoint from 0, and bounded by the hyperplane orthogonal to  $U$  passing through  $-U/\|U\|^2$ . The proof of item (3) is now complete.

(4) Let  $\xi \in \mathbb{R}^r$  be a nonzero vector. The associated subgroup  $(\mathbb{R}\xi) \times \mathbb{R}^n$  is isomorphic to  $\mathbb{R} \times_\delta \mathbb{R}^n$ , where  $\delta \in \text{Der}(\mathbb{R}^n)$  is the derivation  $\text{diag}(\varpi_1(\xi), \dots, \varpi_n(\xi))$ . Such a group is quasi-isometric to  $\mathbb{H}_{\mathbb{R}}^{n+1}$  if and only if  $\delta$  is a multiple of  $-I_n$  [Pansu 2007; Cornuier and Tessera 2011]. Therefore the existence of a  $\xi$  as in the statement is equivalent to the existence of a  $U \in \mathbb{R}^r$  such that  $\varpi_i(U) = -1$  for every  $i \in I$ . Consider again the vectors  $v_i \in \mathbb{R}^r$  such that  $\varpi_i = \langle \cdot, v_i \rangle$ , where  $\langle \cdot, \cdot \rangle$  is a scalar product. One has  $\varpi_i(U) = -1$  for every  $i \in I$  if, and only if, every  $v_i$  belongs to the subset defined by the equation  $\langle U, \cdot \rangle = -1$ , ie to the affine hyperplane which is orthogonal to  $U$  and which passes through  $-U/\|U\|^2$ .  $\square$

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