Anti De Sitter Deformation of Quaternionic Analysis and the Second Order Pole

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Abstract

This is a continuation of a series of papers [FL1, FL2, FL3], where we develop quaternionic analysis from the point of view of representation theory of the conformal Lie group and its Lie algebra. In this paper we continue to study the quaternionic analogues of Cauchy’s formula for the second order pole. These quaternionic analogues are closely related to regularization of infinities of vacuum polarization diagrams in four-dimensional quantum field theory. In order to add some flexibility, especially when dealing with Cauchy’s formula for the second order pole, we introduce a one-parameter deformation of quaternionic analysis.

This deformation of quaternions preserves conformal invariance and has a geometric realization as anti de Sitter space sitting inside the five-dimensional Euclidean space. We show that many results of quaternionic analysis – including the Cauchy-Fueter formula – admit a simple and canonical deformation. We conclude this paper with a deformation of the quaternionic analogues of Cauchy’s formula for the second order pole.

1 Introduction

Let \( \mathbb{H} \) denote the algebra of quaternions

\[
\mathbb{H} = \mathbb{R} \oplus i\mathbb{R} \oplus j\mathbb{R} \oplus k\mathbb{R}
\]

with the norm

\[
N(X) = (x^0)^2 + (x^1)^2 + (x^2)^2 + (x^3)^2, \quad X = x^0 + ix^1 + jx^2 + kx^3 \in \mathbb{H}.
\]

Since the early days of quaternionic analysis, when the quaternionic analogue of complex holomorphic functions was introduced, there was a fundamental question about the natural quaternionic analogue of the ring structure of holomorphic functions\(^1\). In particular, one can ask what is the quaternionic version of the ring of polynomials \( \mathbb{C}[z] \) and Laurent polynomials \( \mathbb{C}[z, z^{-1}] \). The representation theoretic approach that we have developed in [FL1, FL2, FL3] suggests the most naive candidates for an answer: \( \mathbb{H} \)-valued polynomial functions on \( \mathbb{H} \) and \( \mathbb{H}^\times = \{X \in \mathbb{H}; X \neq 0\} \) respectively:

\[
\mathbb{H}[x^0, x^1, x^2, x^3] \quad \text{and} \quad \mathbb{H}[x^0, x^1, x^2, x^3, N(X)^{-1}].
\]

Another option is just to consider \( \mathbb{R} \)-valued polynomial functions on \( \mathbb{H} \) and \( \mathbb{H}^\times \):

\[
\mathbb{R}[x^0, x^1, x^2, x^3] \quad \text{and} \quad \mathbb{R}[x^0, x^1, x^2, x^3, N(X)^{-1}].
\]

\(^1\)Some readers may point out the Cauchy-Kovalevskaya product of quaternionic regular functions. But this operation is not satisfactory, since it does not have good invariance properties with respect to the conformal group action.
Clearly, all four of these spaces of functions have natural ring structures. However, these functions are typically neither regular nor harmonic, so all the regular quaternionic structure is lost. Representation theory asserts that all four quaternionic rings yield the so-called middle series of representations of the conformal Lie algebra $\mathfrak{sl}(2, \mathbb{H}) \cong \mathfrak{so}(5, 1)$ and that there are intertwining maps from tensor products of left regular and right regular polynomials into the two rings (1) and from the tensor products of harmonic polynomials into the two rings (2). It is also natural to complexify the quaternions

$$\mathbb{H}_C = \mathbb{H} \otimes_{\mathbb{R}} \mathbb{C} = 1C \oplus iC \oplus jC \oplus kC$$

and the spaces of polynomial functions on them (1) and (2). This brings us to the main objects of our study:

$$\mathcal{W}^+ = \mathbb{H}_C[z^0, z^1, z^2, z^3],$$

$$\mathcal{W} = \mathbb{H}_C[z^0, z^1, z^2, z^3, N(Z)^{-1}],$$

$$\mathcal{K}^+ = \mathbb{C}[z^0, z^1, z^2, z^3],$$

$$\mathcal{K} = \mathbb{C}[z^0, z^1, z^2, z^3, N(Z)^{-1}]$$

– the two versions of the rings of ordinary and Laurent polynomials in one complex variable.

The relation between the quaternionic ring (5) and harmonic functions yields a reproducing integral formula for functions in $\mathcal{K}^+$. On the other hand, the relation between the ring (3) and the regular functions is similar, but instead of a reproducing formula we get an integral expression for a certain second order differential operator

$$M_x : \mathcal{W}^+ \to \mathcal{W}^+, \quad M_x f = \nabla f \nabla - \Box f^+.$$  

(The operator $M_x$ is directly related to the solutions of the Maxwell equations for the gauge potential.) All of these formulas can be regarded as quaternionic analogues of the Cauchy’s formula for the second order pole

$$f'(z_0) = \frac{1}{2\pi i} \oint \frac{f(z) dz}{(z - z_0)^2}$$

(see [FL1] for details). The corresponding formulas for $\mathcal{W}$ and $\mathcal{K}$ are more involved and are the main subject of this paper. They require certain regularizations of infinities which are well known in four-dimensional quantum field theory as “vacuum polarizations” in spinor and scalar cases respectively. They are usually encoded by the Feynman diagrams shown in Figure 1 and play a key role in renormalization theory (see, for example, [Sm]).

In order to explain our reproducing formula in the scalar case, we recall the space $\mathcal{H}$ of harmonic functions on $\mathbb{H}^\times$. It decomposes into two irreducible components:

$$\mathcal{H} = \mathcal{H}^- \oplus \mathcal{H}^+$$

Figure 1: Vacuum polarization diagrams
with respect to the action of the conformal algebra $\mathfrak{sl}(2, \mathbb{H})$. Similarly, we can decompose $\mathcal{K}$ into three irreducible components:

$$\mathcal{K} = \mathcal{K}^- \oplus \mathcal{K}^0 \oplus \mathcal{K}^+. \quad (8)$$

The spaces $\mathcal{K}^+$ and $\mathcal{K}^-$ have already appeared in [FL1], but the appearance of $\mathcal{K}^0$ in quaternionic analysis is new. We study equivariant embeddings of $\mathcal{K}^-$, $\mathcal{K}^0$, and $\mathcal{K}^+$ into tensor products $\mathcal{H}^\pm \otimes \mathcal{H}^\pm$. The cases $\mathcal{K}^-$ and $\mathcal{K}^+$ are fairly straightforward, but the case of $\mathcal{K}^0$ – which is the core of the scalar vacuum polarization – is more subtle. As a consequence of these equivariant embeddings, we obtain projectors of $\mathcal{K}$ onto its irreducible components. Using these projectors we get a reproducing formula for all functions in $\mathcal{K}$, which may be loosely stated as follows. Let

$$ (I_1 f)(Z_1, Z_2) = \frac{i}{2\pi^3} \int_{W \in U(2)} \frac{f(W) \, dV}{N(W - Z_1) \cdot N(W - Z_2)}, \quad f \in \mathcal{K}, \ Z_1, Z_2 \in \mathbb{D}^+ \sqcup \mathbb{D}^-, $$

where $\mathbb{D}^+$ and $\mathbb{D}^-$ are two certain open regions in $\mathbb{H}_\mathbb{C}$ both having $U(2)$ as their Shilov boundary. Then

$$ f(Z) = \lim_{Z_1, Z_2 \to Z} (I_1 f)(Z_1, Z_2) - \lim_{Z_1, Z_2 \to Z} (I_1 f)(Z_1, Z_2) $$

$$ - \lim_{Z_1, Z_2 \to Z} (I_1 f)(Z_1, Z_2) + \lim_{Z_1, Z_2 \to Z} (I_1 f)(Z_1, Z_2), \quad f \in \mathcal{K}, \ Z \in U(2). \quad (9) $$

(see Remark 16). A similar formula can be deduced for the operator $\text{M} \chi$ acting on $\mathcal{W}$.

The treatment of the projector onto $\mathcal{K}^0$ and the resulting reproducing formula are not completely satisfactory, since the points $Z_1$ and $Z_2$ belong to the non-intersecting domains $\mathbb{D}^+$ and $\mathbb{D}^-$. This phenomenon is well known in physics, where it results in the divergence of the Feynman integral corresponding to the scalar vacuum polarization diagram. Physicists have several methods to achieve this isolation of singularity involving introduction of an auxiliary parameter. Depending on the method, this auxiliary parameter can be interpreted as dimension or mass. The former method is incompatible with representation theoretic approach and the latter is better from our point of view, but still breaks the conformal symmetry down to the famous Poincare group. There is, however, a third way to introduce an auxiliary parameter while fully preserving the conformal invariance – namely via anti de Sitter deformation of the flat Minkowski space. This is the method we pursue in the second part of the paper to develop a deformation of quaternionic analysis. First of all, we define a one-parameter family of conformal Laplacians

$$ \tilde{\Box}_\mu = \Box + \mu^2 (\text{deg}^2 + \text{deg}) $$

depending on a real parameter $\mu$, where $\text{deg}$ denotes the degree operator plus identity and $\Box$ is the ordinary Laplacian on $\mathbb{H}$. As usual, the deformed Laplacian admits a quaternionic factorization into two first order differential operators

$$ \tilde{\Box}_\mu = \tilde{\nabla}_\mu (\tilde{\nabla}_\mu - \mu) = \tilde{\nabla}_\mu (\tilde{\nabla}_\mu + \mu), \quad (11) $$

where the arrows indicate that the operator $\tilde{\nabla}_\mu$ is applied to functions on the left and $\tilde{\nabla}_\mu$ is applied on the right. This factorization allows us to define a one-parameter family of left and right regular functions by the requirement

$$ \tilde{\nabla}_\mu f = 0 \quad \text{and} \quad \tilde{g} \tilde{\nabla}_\mu = 0. $$
Then we prove analogues of Cauchy-Fueter and Poisson formulas as well as generalize certain other constructions and results from quaternionic analysis. In particular, the Poisson kernel \( N(X - Y)^{-1} \) is replaced by the following family of kernels depending on \( \mu \)

\[
\frac{1}{\langle \hat{X} - \hat{Y}, X - Y \rangle_{1,4}},
\]

where

\[
\hat{X} = (\sqrt{\mu^{-2} + N(X)}, x^0, x^1, x^2, x^3), \quad \hat{Y} = (\sqrt{\mu^{-2} + N(Y)}, y^0, y^1, y^2, y^3)
\]

and the 5-dimensional space \( \mathbb{R}^{1,4} \) is equipped with an indefinite inner product

\[
\langle W, W' \rangle_{1,4} = w^0 w'^0 - w^1 w'^1 - w^2 w'^2 - w^3 w'^3 - w^4 w'^4,
\]

\( W = (w^0, w^1, w^2, w^3, w^4) \), \( W' = (w'^0, w'^1, w'^2, w'^3, w'^4) \) \( \in \mathbb{R}^{1,4} \). After developing basics of the anti de Sitter deformation of quaternionic analysis we turn to the treatment of the second order pole.

As the expression for the reproducing kernel (12) indicates, various one-parameter generalizations of results from quaternionic analysis admit a natural geometric interpretation when we identify the space of quaternions with a single sheet of a two-sheeted hyperboloid in \( \mathbb{R}^{1,4} \). This hyperboloid is known to physicists as the anti de Sitter space. Thus the anti de Sitter space-time geometry – which has been extensively studied by physicists (see, for example, [BGMT] and references therein) – naturally provides a one-parameter deformation of (classical) quaternionic analysis. We obtain, in particular, a deformation of the representations \( \mathcal{H}^\pm_\mu \), \( \mathcal{K}^\pm_\mu \) and \( \mathcal{K}^0_\mu \) of the conformal Lie algebra and find projectors onto these spaces. This brings us back to our original motivation of the one-parameter deformation of quaternionic analysis – finding a representation-theoretic interpretation of the regularization in quantum field theory. This question will be addressed in a subsequent work.

The paper consists of two parts related by a common motivation of development of quaternionic analysis using representation-theoretic methods. In Sections 2-8 we study structures related to the second order pole and in Sections 9-17 we develop the one-parameter deformation of quaternionic analysis using geometry of the anti de Sitter space. In Section 2 we summarize the results of quaternionic analysis that are used in this article and, in particular, introduce the representation \( (\rho_1, \mathcal{K}) \) of the conformal algebra \( \mathfrak{gl}(2, \mathbb{H}_\mathbb{C}) \cong \mathfrak{gl}(4, \mathbb{C}) \) which is one of the main subjects of this work. In Section 3 we give explicit \( K \)-types of \( (\rho_1, \mathcal{K}) \), and in Section 4 we show that the representation \( (\rho_1, \mathcal{K}) \) decomposes into three irreducible components (8) (Theorem 7). We also prove that the subspaces \( \mathcal{K}^- \), \( \mathcal{K}^0 \) and \( \mathcal{K}^+ \) are the images under the natural multiplication maps of, respectively, \( \mathcal{H}^- \otimes \mathcal{H}^- \), \( \mathcal{H}^- \otimes \mathcal{H}^+ \) and \( \mathcal{H}^+ \otimes \mathcal{H}^+ \) (Lemma 8). In Section 5 we make a formal calculation of the reproducing kernel for \( \mathcal{K}^0 \). (Note that the reproducing kernels for \( \mathcal{K}^+ \) and \( \mathcal{K}^- \) were computed in [FL1].) In Section 6 we study conformally invariant embeddings of the irreducible components \( \mathcal{K}^\pm \) and \( \mathcal{K}^0 \) into tensor products \( \mathcal{H}^\pm \otimes \mathcal{H}^\pm \), the case of \( \mathcal{K}^0 \) being more subtle, and, as a consequence of these embeddings, we obtain projectors of \( \mathcal{K} \) onto its irreducible components (Theorem 12, Corollary 14 and Theorem 15). In Section 7 we give a new derivation of the identification of the one-loop Feynman diagram with the integral kernels of the projection operators

\[
P^+ : \mathcal{H}^+ \otimes \mathcal{H}^+ \to \mathcal{K}^+ \hookrightarrow \mathcal{H}^+ \otimes \mathcal{H}^+ \quad \text{and} \quad P^- : \mathcal{H}^- \otimes \mathcal{H}^- \to \mathcal{K}^- \hookrightarrow \mathcal{H}^- \otimes \mathcal{H}^-\]

(cf. [FL1]). In Section 8 we realize the spaces \( \mathcal{K}^\pm \), \( \mathcal{K}^0 \) as well as the results of Section 6 in the setting of the Minkowski space \( \mathbb{M} \). In the second part of the paper, Section 9, we introduce the anti de Sitter deformation of the space of quaternions \( \mathbb{H} \) together with the conformal Laplacian.
(10). Then in Section 10 we describe the action of the conformal algebra \( so(1,5) \) on the kernel of the conformal Laplacian. In Section 11 we find simple extensions of the elements of the kernel to \( \mathbb{R}^{1,4} \) as solutions of the wave equation. In Section 12 we introduce a space \( \mathcal{H}_\mu \) consisting of the \( K \)-finite elements of the kernel of the conformal Laplacian. Similarly to (7), we have a decomposition into irreducible components \( \mathcal{H}_\mu = \mathcal{H}_\mu^+ \oplus \mathcal{H}_\mu^- \). In Section 13 we prove an analogue of the Poisson formula for the solutions of \( \tilde{\mathcal{H}}_\mu \varphi = 0 \) (Theorem 32). In Section 14 we factor the conformal Laplacian as a product of two Dirac-type operators (11). In Sections 15 and 16 we proceed to study deformed quaternionic regular functions. We prove analogues of the Cauchy’s Theorem and the Cauchy-Fueter formula in the deformed setting (Corollary 38 and Theorem 41). Finally, in Section 17 we introduce a deformation \( \mathcal{K}_\mu \) of the space \( \mathcal{K} \) associated with the second order pole, similarly to (8), decompose it into a direct sum \( \mathcal{H}_\mu^- \oplus \mathcal{H}_\mu^0 \oplus \mathcal{H}_\mu^+ \) and obtain projectors onto these direct summands.

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2 Preliminaries

We recall some notations from [FL1]. Let \( \mathbb{H}_C \) denote the space of complexified quaternions: \( \mathbb{H}_C = \mathbb{H} \otimes \mathbb{C} \), it can be identified with the algebra of \( 2 \times 2 \) complex matrices:

\[
\mathbb{H}_C = \mathbb{H} \otimes \mathbb{C} \simeq \left\{ Z = \begin{pmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{pmatrix} ; z_{ij} \in \mathbb{C} \right\} = \left\{ Z = \begin{pmatrix} z^0 & iz^3 \\ -iz^1 - z^2 & z^0 + iz^3 \end{pmatrix} ; z^k \in \mathbb{C} \right\}.
\]

For \( Z \in \mathbb{H}_C \), we write

\[
N(Z) = \det \begin{pmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{pmatrix} = z_{11}z_{22} - z_{12}z_{21} = (z^0)^2 + (z^1)^2 + (z^2)^2 + (z^3)^2
\]

and think of it as the norm of \( Z \). We denote by \( \mathbb{H}_C^\times \) the group of invertible complexified quaternions:

\[
\mathbb{H}_C^\times = \{ Z \in \mathbb{H}_C ; N(Z) \neq 0 \}.
\]

Clearly, \( \mathbb{H}_C^\times \simeq GL(2, \mathbb{C}) \). We realize \( U(2) \) as a subgroup of \( \mathbb{H}_C^\times \):

\[
U(2) = \{ Z \in \mathbb{H}_C ; Z^* = Z^{-1} \},
\]

where \( Z^* \) denotes the complex conjugate transpose of a complex matrix \( Z \). For \( R > 0 \), we set

\[
U(2)_R = \{ RZ ; Z \in U(2) \}
\]

and orient it as in [FL1] so that \( \int_{U(2)_R} \frac{dV}{N(Z)^2} = -2\pi^2 i \), where \( dV \) is a holomorphic 4-form defined by

\[
dV = dz^0 \wedge dz^1 \wedge dz^2 \wedge dz^3 = \frac{1}{4} dz_{11} \wedge dz_{12} \wedge dz_{21} \wedge dz_{22}.
\]

Recall that a group \( GL(2, \mathbb{H}_C) \simeq GL(4, \mathbb{C}) \) acts on \( \mathbb{H}_C \) by fractional linear (or conformal) transformations:

\[
h : Z \mapsto (aZ + b)(cZ + d)^{-1} = (a' - Zc')^{-1}(-b' + Zd'), \quad Z \in \mathbb{H}_C,
\]

where \( h = \left( \begin{smallmatrix} a & b \\ c & d \end{smallmatrix} \right) \in GL(2, \mathbb{H}_C) \) and \( h^{-1} = \left( \begin{smallmatrix} a' & b' \\ c' & d' \end{smallmatrix} \right) \).

For convenience we recall Lemmas 10 and 61 from [FL1]:
Lemma 1. For \( h = (a \ b \ c \ d) \in GL(2, \mathbb{H}_C) \) with \( h^{-1} = (a' \ b' \ c' \ d') \), let \( \tilde{Z} = (aZ + b)(cZ + d)^{-1} \) and \( \tilde{W} = (aW + b)(cW + d)^{-1} \). Then

\[
(\tilde{Z} - \tilde{W}) = (a' - Wc')^{-1} \cdot (Z - W) \cdot (cZ + d)^{-1}
= (a' - Zc')^{-1} \cdot (Z - W) \cdot (cW + d)^{-1}.
\]

Lemma 2. Let \( d\tilde{V} \) denote the pull-back of \( dV \) under the map \( Z \mapsto (aZ + b)(cZ + d)^{-1} \), where \( h = (a \ b \ c \ d) \in GL(2, \mathbb{H}_C) \) and \( h^{-1} = (a' \ b' \ c' \ d') \). Then

\[
dV = N(cZ + d)^2 \cdot N(a' - Zc')^2 \, d\tilde{V}.
\]

We often use the matrix coefficient functions of \( SU(2) \) described by equation (27) of [FL1] (cf. [V]):

\[
t^j_{m,n}(Z) = \frac{1}{2\pi i} \oint (sz_{11} + z_{21})^{l-m} (sz_{12} + z_{22})^{l+m} s^{-l-n} \frac{ds}{s}, \quad l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots, \quad m, n \in \mathbb{Z} + l,
\]

\[
-l \leq m, n \leq l,
\]

\[
Z = (z_{11} \ z_{12} \ z_{21} \ z_{22}) \in \mathbb{H}_C, \text{ the integral is taken over a loop in } \mathbb{C} \text{ going once around the origin in the counterclockwise direction.}
\]

We regard these functions as polynomials on \( \mathbb{H}_C \). For future use we state the multiplicativity property of matrix coefficients

\[
t^l_{m,n}(Z_1 Z_2) = \sum_{j=-l}^l t^j_{m,n}(Z_1) \cdot t^j_{m,n}(Z_2).
\]

It is also useful to recall that

\[
t^l_{m,n}(Z^{-1}) = t^l_{m,n}(Z^+) \cdot N(Z)^{-2l} \text{ is proportional to } t^l_{-m,-n}(Z) \cdot N(Z)^{-2l}.
\]

As in Section 2 of [FL2], we consider the space of \( \mathbb{C} \)-valued functions on \( \mathbb{H}_C \) (possibly with singularities) which are holomorphic with respect to the complex variables \( z^0, z^1, z^2, z^3 \) or \( z_{11}, z_{12}, z_{21}, z_{22} \) and harmonic, i.e. satisfying \( \Box \varphi = 0 \), where

\[
\Box = \frac{\partial^2}{(\partial z^0)^2} + \frac{\partial^2}{(\partial z^1)^2} + \frac{\partial^2}{(\partial z^2)^2} + \frac{\partial^2}{(\partial z^3)^2} = 4 \left( \frac{\partial^2}{\partial z_{11} \partial z_{22}} - \frac{\partial^2}{\partial z_{12} \partial z_{21}} \right).
\]

We denote this space by \( \tilde{\mathcal{H}} \). Then the conformal group \( GL(2, \mathbb{H}_C) \simeq GL(4, \mathbb{C}) \) acts on \( \tilde{\mathcal{H}} \) by two slightly different actions:

\[
\pi^0_h(h) : \varphi(Z) \mapsto (\pi^0_h(h) \varphi)(Z) = \frac{1}{N(cZ + d)} \cdot \varphi((aZ + b)(cZ + d)^{-1}),
\]

\[
\pi^0_r(h) : \varphi(Z) \mapsto (\pi^0_r(h) \varphi)(Z) = \frac{1}{N(a' - Zc')} \cdot \varphi((a' - Zc')^{-1}(-b' + Zd')), \quad \forall Z \in \mathbb{H}_C,
\]

where \( h = (a \ b \ c \ d) \in GL(2, \mathbb{H}_C) \) and \( h^{-1} = (a' \ b' \ c' \ d') \). We have

\[
(aZ + b)(cZ + d)^{-1} = (a' - Zc')^{-1}(-b' + Zd'), \quad \forall Z \in \mathbb{H}_C,
\]

and these two actions coincide on \( SL(2, \mathbb{H}_C) \simeq SL(4, \mathbb{C}) \), which is defined as the connected Lie subgroup of \( GL(2, \mathbb{H}_C) \) with Lie algebra

\[
\mathfrak{sl}(2, \mathbb{H}_C) = \{ x \in \mathfrak{gl}(2, \mathbb{H}_C) ; \ \text{Re}(\text{Tr} \ x) = 0 \} \simeq \mathfrak{sl}(4, \mathbb{C}).
\]
We introduce two spaces of harmonic polynomials:

\[ \mathcal{H}^+ = \tilde{\mathcal{H}} \cup \mathbb{C}[z_{11}, z_{12}, z_{21}, z_{22}] \]
\[ \mathcal{H} = \tilde{\mathcal{H}} \cup \mathbb{C}[z_{11}, z_{12}, z_{21}, z_{22}, N(Z)^{-1}] \]

and the space of harmonic polynomials regular at infinity:

\[ \mathcal{H}^- = \{ \varphi \in \tilde{\mathcal{H}}; N(Z)^{-1} \cdot \varphi(Z^{-1}) \in \mathcal{H}^+ \} \]

Then

\[ \mathcal{H} = \mathcal{H}^- \oplus \mathcal{H}^+ \]
\[ \mathcal{H}^+ = \text{Span}\{ t^l_{m}(Z) \} \]
\[ \mathcal{H}^- = \text{Span}\{ t^l_{m}(Z) \cdot N(Z)^{-(2l+1)} \} \]

In particular, there are no homogeneous harmonic functions in \( \mathbb{C}[z_{11}, z_{12}, z_{21}, z_{22}, N(Z)^{-1}] \) of degree \(-1\). Differentiating the actions \( \pi_l^1 \) and \( \pi_l^0 \), we obtain actions of \( \mathfrak{gl}(2, \mathbb{H}_\mathbb{C}) \simeq \mathfrak{gl}(4, \mathbb{C}) \) which preserve the spaces \( \mathcal{H} \), \( \mathcal{H}^- \) and \( \mathcal{H}^+ \). By abuse of notation, we denote these Lie algebra actions by \( \pi^0 \) and \( \pi^r \) respectively. They are described in Subsection 3.2 of [FL2].

By Theorem 28 in [FL1], for each \( R > 0 \), we have a bilinear pairing between \( (\pi^0, \mathcal{H}) \) and \( (\pi^r, \mathcal{H}) \):

\[ (\varphi_1, \varphi_2) = \int_{S^3_R} (\widetilde{\text{deg}} \varphi_1)(Z) \cdot \varphi_2(Z) \frac{dS}{R} \]

where \( S^3_R \subset \mathbb{H} \) is the three-dimensional sphere of radius \( R \) centered at the origin

\[ S^3_R = \{ X \in \mathbb{H}; N(X) = R^2 \} \]

\( dS \) denotes the usual Euclidean volume element on \( S^3_R \), and \( \widetilde{\text{deg}} \) denotes the degree operator plus identity:

\[ \widetilde{\text{deg}} f = f + \text{deg} f = f + z_{11} \frac{\partial f}{\partial z_{11}} + z_{12} \frac{\partial f}{\partial z_{12}} + z_{21} \frac{\partial f}{\partial z_{21}} + z_{22} \frac{\partial f}{\partial z_{22}} \]

When this pairing is restricted to \( \mathcal{H}^+ \times \mathcal{H}^- \), it is \( \mathfrak{gl}(2, \mathbb{H}_\mathbb{C}) \)-invariant, independent of the choice of \( R > 0 \), non-degenerate and antisymmetric:

\[ (\varphi_1, \varphi_2)_R = -(\varphi_2, \varphi_1)_R \]

\( \varphi_1 \in \mathcal{H}^+, \varphi_2 \in \mathcal{H}^- \).

We have the following orthogonality relations with respect to the pairing (16):

\[ (t^l_{m'}(Z), t^l_{m}(Z^-1) \cdot N(Z)^{-1})_R = -(t^l_{m}(Z^-1) \cdot N(Z)^{-1}, t^{l'}_{m'}(Z))_R = \delta_{l l'} \delta_{m m'} \delta_{n n'}, \]

where the indices \( l, m, n \) are \( l = 0, 1, 2, \ldots \), \( m, n \in \mathbb{Z} + l \), \( -l \leq m, n \leq l \) and similarly for \( l', m', n' \).

Let \( \tilde{K} \) denote the space of \( \mathbb{C} \)-valued functions on \( \mathbb{H}_\mathbb{C} \) (possibly with singularities) which are holomorphic with respect to the complex variables \( z_{11}, z_{12}, z_{21}, z_{22} \). (There are no differential equations imposed on functions in \( \tilde{K} \) whatsoever.) We recall the action of \( GL(2, \mathbb{H}_\mathbb{C}) \) on \( \tilde{K} \) given by equation (49) in [FL1]:

\[ \rho_1(h) : f(Z) \mapsto (\rho_1(h)f)(Z) = f((aZ + b)(cZ + d)^{-1}) \]

\[ \frac{N(cZ + d) \cdot N(a' - Zd')}{N(cZ + d)} \]
where $h = (a, b, c, d) \in GL(2, \mathbb{H}_\mathbb{C})$ and $h^{-1} = (a', b', c', d')$. We have a natural $GL(2, \mathbb{H}_\mathbb{C})$-equivariant multiplication map

$$M : (\pi^0_t, \widetilde{\mathcal{H}}) \otimes (\pi^0_r, \widetilde{\mathcal{H}}) \rightarrow (\rho_1, \widetilde{\mathcal{K}})$$

which is determined on pure tensors by

$$M( \varphi_1(Z_1) \otimes \varphi_2(Z_2)) = (\varphi_1 \cdot \varphi_2)(Z), \quad \varphi_1, \varphi_2 \in \widetilde{\mathcal{H}}.$$ Differentiating the $\rho_1$-action, we obtain an action of $\mathfrak{gl}(2, \mathbb{H}_\mathbb{C}) \simeq \mathfrak{gl}(4, \mathbb{C})$. For convenience we recall Lemma 68 from [FL1].

**Lemma 3.** Let $\partial = (\partial_{i1}, \partial_{i2}) = \frac{1}{2} \nabla$, where $\partial_{ij} = \frac{\partial}{\partial x_{ij}}$. The Lie algebra action $\rho_1$ of $\mathfrak{gl}(2, \mathbb{H}_\mathbb{C})$ on $\widetilde{\mathcal{K}}$ is given by

$$\rho_1 \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix} : f \mapsto \text{Tr}(A \cdot (-Z \cdot \partial f - f))$$

$$\rho_1 \begin{pmatrix} 0 & B \\ 0 & 0 \end{pmatrix} : f \mapsto \text{Tr}(B \cdot (-\partial f))$$

$$\rho_1 \begin{pmatrix} C & 0 \\ 0 & 0 \end{pmatrix} : f \mapsto \text{Tr}(C \cdot (Z \cdot \partial f) \cdot Z + 2ZF) = \text{Tr}(C \cdot (Z \cdot \partial(Zf)))$$

$$\rho_1 \begin{pmatrix} 0 & 0 \\ 0 & D \end{pmatrix} : f \mapsto \text{Tr}(D \cdot ((\partial f) \cdot Z + f)) = \text{Tr}(D \cdot (\partial(Zf) - f)).$$

This lemma implies that $\mathfrak{gl}(2, \mathbb{H}_\mathbb{C})$ preserves the spaces

$$\mathcal{K}^+ = \{\text{polynomial functions on } \mathbb{H}_\mathbb{C}\} = \mathbb{C}[z_{11}, z_{12}, z_{21}, z_{22}] \quad \text{and}$$

$$\mathcal{K} = \{\text{polynomial functions on } \mathbb{H}_\mathbb{C}^\times\} = \mathbb{C}[z_{11}, z_{12}, z_{21}, z_{22}, N(Z)^{-1}].$$

Define

$$\mathcal{K}^- = \left\{ f \in \mathcal{K} ; \rho_1 \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} f(Z) = N(Z)^{-2} \cdot f(Z^{-1}) \in \mathcal{K}^+ \right\},$$

this is another $\mathfrak{gl}(2, \mathbb{H}_\mathbb{C})$-invariant space. Comparing this with Definition 16 in [FL1], we can say that $\mathcal{K}^-$ consists of those elements of $\mathcal{K}$ that are regular at infinity according to the $\rho_1$-action of $GL(2, \mathbb{H}_\mathbb{C})$. Note that $\mathcal{K}^- \oplus \mathcal{K}^+$ is a proper subspace of $\mathcal{K}$.

Next we describe an invariant bilinear pairing on $\mathcal{K}$. Recall Proposition 69 from [FL1]:

**Proposition 4.** The representation $(\rho_1, \mathcal{K})$ of $\mathfrak{gl}(2, \mathbb{H}_\mathbb{C})$ has a non-degenerate symmetric bilinear pairing

$$\langle f_1, f_2 \rangle = \frac{i}{2\pi^3} \int_{U(2)R} f_1(Z) \cdot f_2(Z) \, dV, \quad f_1, f_2 \in \mathcal{K}, \quad (18)$$

where $R > 0$. This bilinear pairing is $\mathfrak{gl}(2, \mathbb{H}_\mathbb{C})$-invariant and independent of the choice of $R > 0$.

We have the following orthogonality relations with respect to the pairing (18):

$$\langle t^{k}_m, t^{l'}_{m'}(Z) \cdot N(Z)^k, t^{l}_m(Z^{-1}) \cdot N(Z)^{-k-2} \rangle = \frac{1}{2l + 1} \delta_{kk'} \delta_{mm'} \delta_{nn'}, \quad (19)$$

where the indices $k, l, m, n$ are $k \in \mathbb{Z}, l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots, m, n \in \mathbb{Z} + l, -l \leq m, n \leq l$ and similarly for $k', l', m', n'$.

We know from [JV] and [FL1] that the representations $(\rho_1, \mathcal{K}^+)$ and $(\rho_1, \mathcal{K}^-)$ are $\mathbb{C}$-linear dual to each other with respect to (18), irreducible when restricted to $\mathfrak{sl}(2, \mathbb{H}_\mathbb{C})$ and possess
inner products which make them unitary representations of the real form \( su(2, 2) \) of \( sl(2, \mathbb{H}_C) \), where we regard \( su(2, 2) \) and \( u(2, 2) \) as subalgebras of \( gl(2, \mathbb{H}_C) \) as in (20).

We often regard the group \( U(2, 2) \) as a subgroup of \( GL(2, \mathbb{H}_C) \) as described in Subsection 3.5 of [FL1]. That is

\[
U(2, 2) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in GL(2, \mathbb{H}_C) ; \ a, b, c, d \in \mathbb{H}_C, \ a^*a = 1 + c^*c, \ d^*d = 1 + b^*b, \ a^*b = c^*d \right\}.
\]

The Lie algebra of \( U(2, 2) \) is

\[
u(2, 2) = \left\{ \begin{pmatrix} A & B \\ B^* & D \end{pmatrix} \in gl(2, \mathbb{H}_C) ; \ A, B, D \in \mathbb{H}_C, \ A = -A^*, D = -D^* \right\}.
\] (20)

The maximal compact subgroup of \( U(2, 2) \) is

\[
U(2) \times U(2) = \left\{ \begin{pmatrix} a & 0 \\ 0 & d \end{pmatrix} \in GL(2, \mathbb{H}_C) ; \ a, d \in \mathbb{H}_C, \ a^*a = d^*d = 1 \right\}.
\] (21)

The group \( U(2, 2) \) acts on \( \mathbb{H}_C \) by fractional linear transformations (13) preserving \( U(2) \subset \mathbb{H}_C \) and open domains

\[
\mathbb{D}^+ = \{ Z \in \mathbb{H}_C ; \ ZZ^* < 1 \}, \quad \mathbb{D}^- = \{ Z \in \mathbb{H}_C ; \ ZZ^* > 1 \},
\]

where the inequalities \( ZZ^* < 1 \) and \( ZZ^* > 1 \) mean that the matrix \( ZZ^* - 1 \) is negative and positive definite respectively. The sets \( \mathbb{D}^+ \) and \( \mathbb{D}^- \) both have \( U(2) \) as the Shilov boundary.

Similarly, for each \( R > 0 \) we can define a conjugate of \( U(2, 2) \)

\[
U(2, 2)_R = \begin{pmatrix} R & 0 \\ 0 & 1 \end{pmatrix} U(2, 2) \begin{pmatrix} R^{-1} & 0 \\ 0 & 1 \end{pmatrix} \subset GL(2, \mathbb{H}_C).
\]

Each group \( U(2, 2)_R \) is a real form of \( GL(2, \mathbb{H}_C) \), preserves \( U(2, 2)_R \) and open domains

\[
\mathbb{D}^+_R = \{ Z \in \mathbb{H}_C ; \ ZZ^* < R^2 \}, \quad \mathbb{D}^-_R = \{ Z \in \mathbb{H}_C ; \ ZZ^* > R^2 \}. \] (22)

These sets \( \mathbb{D}^+_R \) and \( \mathbb{D}^-_R \) both have \( U(2, 2)_R \) as the Shilov boundary.

3  \( K \)-type Basis of \((\rho_1, \mathcal{K})\)

In this section we describe a convenient basis of \((\rho_1, \mathcal{K})\) consisting of \( K \)-types for the maximal compact subgroup \( U(2) \times U(2) \) of \( U(2, 2) \).

**Proposition 5.** The functions

\[
t_{nm}^l(Z) \cdot N(Z)^k, \quad l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots, \quad m, n = -l, -l + 1, \ldots, l, \quad k = 0, 1, 2, \ldots, \] (23)

form a vector space basis of \( \mathcal{K}^+ = \mathbb{C}[z_{11}, z_{12}, z_{21}, z_{22}] \).

**Proof.** Clearly, the functions \( t_{nm}^l(Z) \cdot N(Z)^k \) are polynomials. From the orthogonality relations (19) it follows that they are linearly independent. It remains to show that they span all of \( \mathcal{K}^+ \). We can do that by comparing the dimensions of the subspaces homogeneous functions of degree \( d \) in \( \mathcal{K}^+ \) and the space spanned by (23).
The number of monomials \( (z_{11})^{\alpha_{11}}(z_{12})^{\alpha_{12}}(z_{21})^{\alpha_{21}}(z_{22})^{\alpha_{22}} \) in \( \mathcal{K}^+ \) with \( \alpha_{11} + \alpha_{12} + \alpha_{21} + \alpha_{22} = d \) is
\[
\binom{d+3}{3} = \frac{(d+3)(d+2)(d+1)}{6}.
\] (24)

On the other hand, for \( k \) and \( l \) fixed, there are exactly \( (2l+1)^2 \) basis elements (23) and they are all homogeneous of degree \( 2l + 2k \). Therefore, the dimension of the subspace of homogeneous functions of degree \( d \) inside the span of (23) is
\[
(d + 1)^2 + (d - 1)^2 + (d - 3)^2 + \ldots.
\] (25)

Finally, it is easy to show by induction that (24) and (25) are in fact equal. \( \square \)

We conclude this section with a decomposition of \((\rho_1, \mathcal{K})\) into \( K \)-types.

**Corollary 6.** The functions
\[
t_l^m(Z) \cdot N(Z)^k, \quad l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots, \quad m, n = -l, -l + 1, \ldots, l, \quad k \in \mathbb{Z},
\]
form a vector space basis of \( \mathcal{K} = \mathbb{C}[z_{11}, z_{12}, z_{21}, z_{22}, N(Z)^{-1}] \).

**Proof.** The functions \( t_l^m(Z) \cdot N(Z)^k \) are linearly independent by (19) and by Proposition 5 span the entire space \( \mathcal{K} \). \( \square \)

## 4 Irreducible Components of \((\rho_1, \mathcal{K})\)

In this section we decompose \((\rho_1, \mathcal{K})\) into irreducible components, identify these irreducible components as images of multiplication maps and describe their unitary structures.

**Theorem 7.** The representation \((\rho_1, \mathcal{K})\) of \( \mathfrak{gl}(2, \mathbb{H}_\mathbb{C}) \) has the following decomposition into irreducible components:
\[
(\rho_1, \mathcal{K}) = (\rho_1, \mathcal{K}^+) \oplus (\rho_1, \mathcal{K}^-) \oplus (\rho_1, \mathcal{K}^0),
\]
where
\[
\mathcal{K}^+ = \mathbb{C} - \text{span of } \{t_l^m(Z) \cdot N(Z)^k; k \geq 0\},
\]
\[
\mathcal{K}^- = \mathbb{C} - \text{span of } \{t_l^m(Z) \cdot N(Z)^k; k \leq -(2l + 2)\},
\]
\[
\mathcal{K}^0 = \mathbb{C} - \text{span of } \{t_l^m(Z) \cdot N(Z)^k; -(2l + 1) \leq k \leq -1\}
\]
(see Figure 2).

**Proof.** Note that the basis elements (23) consist of functions of the kind
\[
f_l(Z) \cdot N(Z)^k, \quad \square f_l(Z) = 0, \quad l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots, \quad k \in \mathbb{Z},
\]
where the functions \( f_l(Z) \) range over a basis of harmonic functions which are polynomials of degree \( 2l \). Recall that we consider \( U(2) \times U(2) \) as a subgroup of \( GL(2, \mathbb{H}_\mathbb{C}) \) via (21). For \( k \) and \( l \) fixed, these functions span an irreducible representation of \( U(2) \times U(2) \), which – when restricted to \( SU(2) \times SU(2) \) – becomes isomorphic to \( V_l \otimes \bar{V}_l \), where \( V_l \) denotes the irreducible representation of \( SU(2) \) of dimension \( 2l + 1 \).
Hence we can write

By direct computation we have:

Lemma 3 describing their action and compute

Conjugating (26) we see that

Therefore,

Next we determine the effect of matrices of the kind \((0 \ B \ 0) \in \mathfrak{gl}(2, \mathbb{H}_\mathbb{C})\) with \(B \in \mathbb{H}_\mathbb{C}\), we use Lemma 3 and compute

To determine the effect of matrices of the kind \((0 \ 0 \ C) \in \mathfrak{gl}(2, \mathbb{H}_\mathbb{C})\) with \(C \in \mathbb{H}_\mathbb{C}\), we use Lemma 3 and compute

By direct computation we have:

\[
\square(Z^+ f_l) = Z^+ \square f_l + 4 \partial f_l
\]

and

Hence we can write

and

with \(\partial f_l\) and \(Z^+ \cdot (\partial^+ f_l) \cdot Z^+ + Z^+ f_l\) being harmonic and having degrees \(2l - 1\) and \(2l + 1\) respectively.

Next we determine the effect of matrices of the kind \((0 \ 0 \ C) \in \mathfrak{gl}(2, \mathbb{H}_\mathbb{C})\) with \(C \in \mathbb{H}_\mathbb{C}\). Again, we use Lemma 3 and compute

Conjugating (26) we see that

Therefore,

\[
Z \cdot \partial(f_l \cdot N(Z)^k) \cdot Z + 2Z f_l \cdot N(Z)^k = Z \cdot \partial(f_l) \cdot Z \cdot N(Z)^k + (k + 2)Z f_l \cdot N(Z)^k.
\]

\[
Z f_l = \frac{Z \cdot (\partial f_l) \cdot Z + Z f_l}{2l + 1} + \frac{\partial^+ f_l \cdot N(Z)}{2l + 1}.
\]

\[
Z \cdot \partial(f_l \cdot N(Z)^k) \cdot Z + 2Z f_l \cdot N(Z)^k
\]

\[
= \frac{2l + k + 2}{2l + 1} (Z \cdot (\partial f_l) \cdot Z + Z f_l) \cdot N(Z)^k + \frac{k + 1}{2l + 1} \partial^+ f_l \cdot N(Z)^{k+1}
\]

Figure 2: Decomposition of \((\rho_1, \mathcal{K})\) into irreducible components

\[
\begin{align*}
&\mathcal{H}^0 \\
&\mathcal{K}^+ \\
&\mathcal{K}^- \\
&Z \\
&2l \\
&k
\end{align*}
\]
with \( Z \cdot (\partial f_i) \cdot Z + Z f_i \) and \( \partial + f_i \) being harmonic and having degrees \( 2l + 1 \) and \( 2l - 1 \) respectively.

The actions of \( \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & B \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 \\ C & 0 \end{pmatrix} \) and \( \begin{pmatrix} 0 & 0 \\ 0 & D \end{pmatrix} \) are illustrated in Figure 3. In the diagram describing \( \rho_1(\begin{pmatrix} 0 & B \\ 0 & 0 \end{pmatrix}) \) the vertical arrow disappears if \( l = 0 \) or \( 2l + k + 1 = 0 \) and the diagonal arrow disappears if \( k = 0 \). Similarly, in the diagram describing \( \rho_1(\begin{pmatrix} 0 & 0 \\ C & 0 \end{pmatrix}) \) the vertical arrow disappears if \( 2l + k + 2 = 0 \) and the diagonal arrow disappears if \( k = -1 \) or \( l = 0 \). This proves that \( \mathcal{K}^+ \), \( \mathcal{K}^- \) and \( \mathcal{K}^0 \) are \( \mathfrak{gl}(2, \mathbb{H}_C) \)-invariant subspaces of \( \mathcal{K} \). Note that

\[
\text{Tr}(Z \cdot \partial f + f) = \text{Tr}\left( z_{11} \partial_{11} f + z_{12} \partial_{12} f + f \right) = (\deg + 2)f,
\]
hence \( Z \cdot (\partial f_i) \cdot Z + Z f_i = (Z \cdot \partial f_i + f) \cdot Z \) and its conjugate \( Z^+ \cdot (\partial f_i) \cdot Z^+ + Z^+ f_i \) are never zero. It follows from (27) and (28) that the subrepresentations \( (\rho_1, \mathcal{K}^+), (\rho_1, \mathcal{K}^-), (\rho_1, \mathcal{K}^0) \) are irreducible with respect to the \( \rho_1 \)-action of \( \mathfrak{gl}(2, \mathbb{H}_C) \).

Our next task is to identify the images under the natural \( \mathfrak{gl}(2, \mathbb{H}_C) \)-equivariant multiplication maps:

\[
M : (\pi^0, \mathcal{H}^\pm) \otimes (\pi^0, \mathcal{H}^\pm) \rightarrow (\rho_1, \mathcal{K})
\]

(29)
sending pure tensors

\[
\varphi_1(Z_1) \otimes \varphi_2(Z_2) \mapsto (\varphi_1 \cdot \varphi_2)(Z).
\]

**Lemma 8.** Under the multiplication maps \( (\pi^0, \mathcal{H}^\pm) \otimes (\pi^0, \mathcal{H}^\pm) \rightarrow (\rho_1, \mathcal{K}) \),

1. The image of \( \mathcal{H}^+ \otimes \mathcal{H}^+ \) in \( \mathcal{K} \) is \( \mathcal{K}^+ \);

2. The image of \( \mathcal{H}^- \otimes \mathcal{H}^- \) in \( \mathcal{K} \) is \( \mathcal{K}^- \);

3. The image of \( \mathcal{H}^- \otimes \mathcal{H}^+ \) in \( \mathcal{K} \) is \( \mathcal{K}^0 \).

**Proof.** Note that the space \( \mathcal{H}^+ \) consists of harmonic polynomials. The product of two polynomials is another polynomial, hence the image of \( \mathcal{H}^+ \otimes \mathcal{H}^+ \) lies in \( \mathcal{K}^+ \). Since \( (\rho_1, \mathcal{K}) \) is irreducible, the image is all of \( \mathcal{K}^+ \).

Applying \( \pi^0_l \otimes \pi^0_m \)(\( \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \)) to the left hand side of \( \mathcal{H}^+ \otimes \mathcal{H}^+ \rightarrow \mathcal{K}^+ \) and \( \rho_1(\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}) \) to the right hand side, we see that the image of \( \mathcal{H}^- \otimes \mathcal{H}^- \) is \( \mathcal{K}^- \).

Let us denote by \( J \) the image of \( \mathcal{H}^- \otimes \mathcal{H}^+ \) in \( \mathcal{K} \). Clearly, \( J \) contains the function \( N(Z)^{-1} \), which generates \( \mathcal{K}^0 \). Hence \( \mathcal{K}^0 \subset J \). It remains to show that \( J \subset \mathcal{K}^0 \). By Theorem 7, if \( \mathcal{K}^0 \subset J \), then \( J \) also contains \( \mathcal{K}^+ \) or \( \mathcal{K}^- \) and hence functions \( N(Z)^k \) with \( k \neq -1 \). Thus it is sufficient to prove that \( J \) cannot contain \( N(Z)^k \) with \( k \neq -1 \).

By construction, \( J \) is spanned by

\[
N(Z)^{-(2l+1)} \cdot t_{n, m}^l(Z) \cdot t_{n', m'}^{l'}(Z).
\]

(30)

Note that if \( V_l \) and \( V_{l'} \) are two irreducible representations of \( SU(2) \) of dimensions \( 2l + 1 \) and \( 2l' + 1 \) respectively, then their tensor product contains a copy of the trivial representation if and only if \( l = l' \). This means that a linear combination of the functions (30) can express \( N(Z)^k \) only if \( l = l' \). But then the homogeneity degree of (30) is \(-2\). Therefore, \( N(Z)^k \notin J \) if \( k \neq -1 \).
As we have mentioned, the representations \( (\rho_1, \mathcal{K}^+) \) and \( (\rho_1, \mathcal{K}^-) \) are \( \mathbb{C} \)-linear dual to each other with respect to (18). On the other hand, the \( \mathbb{C} \)-linear dual of \( (\rho_1, \mathcal{K}^0) \) with respect to (18) is \( (\rho_1, \mathcal{K}^0) \) itself. We conclude this section with an explicit description of the unitary structures on \( (\rho_1, \mathcal{K}^+), (\rho_1, \mathcal{K}^-) \) and \( (\rho_1, \mathcal{K}^0) \). Define

\[
(f_1, f_2) = \frac{i}{2\pi^3} \int_{U(2)} f_1(Z) \cdot f_2(Z) \frac{dV}{N(Z)^2}, \quad f_1, f_2 \in \mathcal{K}.
\]

This pairing is an inner product.

**Proposition 9.** The restrictions of \( (\rho_1, \mathcal{K}^+), (\rho_1, \mathcal{K}^-) \) and \( (\rho_1, \mathcal{K}^0) \) to \( \mathfrak{u}(2, 2) \) are unitary with respect to the inner product \((31)\).

**Proof.** We only need to prove that the pairing \((31)\) is \( \mathfrak{u}(2, 2) \)-invariant. It is enough to show that, for all \( h \in \mathfrak{u}(2, 2) \) sufficiently close to the identity element, we have

\[
(f_1, f_2) = (\rho_1(h)f_1, \rho_1(h)f_2), \quad f_1, f_2 \in \mathcal{K}.
\]

If \( h^{-1} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathfrak{u}(2, 2) \), then \( h = \begin{pmatrix} a^* & -c^* \\ b & d^* \end{pmatrix} \). (If \( Z \in \mathbb{H}_\mathbb{C}, Z^* \in \mathbb{H}_\mathbb{C} \) denotes the matrix adjoint of \( Z \) under the standard identification of \( \mathbb{H}_\mathbb{C} \) with \( 2 \times 2 \) complex matrices, see [FL1] for details.)

Writing \( \tilde{Z} = (aZ + b)(cZ + d)^{-1} \) and using Lemma 2 together with the fact that \( U(2) \) preserves \( U(2) = \{ Z \in \mathbb{H}_\mathbb{C}; Z^* = Z^{-1} \} \) we obtain:

\[
-2\pi^3 \cdot (\rho_1(h)f_1, \rho_1(h)f_2)
= \int_{Z \in U(2)} \frac{f_1(\tilde{Z})}{N(cZ + d) \cdot N(a^* + Zb^*)} \cdot \frac{f_2(\tilde{Z})}{N(cZ + d) \cdot N(a^* + Zb^*)} \frac{dV}{N(Z)^2}
= \int_{Z \in U(2)} \frac{f_1(\tilde{Z})}{N(cZ + d) \cdot N(a^* + Zb^*)} \cdot \frac{f_2(\tilde{Z})}{N(cZ + d) \cdot N(a^* + Zb^*)} \frac{dV}{N(Z)^2}
= \int_{Z \in U(2)} \frac{f_1(\tilde{Z})}{N(cZ + d) \cdot N(a^* + Zb^*)} \cdot \frac{f_2(\tilde{Z})}{N(cZ + d) \cdot N(a^* + Zb^*)} \frac{dV}{N(Z)^2}
= -2\pi^3 \cdot (f_1, f_2).
\]

\( \square \)

5 Formal Calculation of the Reproducing Kernel for \( (\rho_1, \mathcal{K}^0) \)

In [FL1], Proposition 27, we computed the reproducing kernels for \( (\rho_1, \mathcal{K}^+) \) and \( (\rho_1, \mathcal{K}^-) \) by finding expansions for \( \frac{1}{N(Z-W)^2} \) in terms of basis functions \((23)\). In both cases the reproducing kernel is \( \frac{1}{N(Z-W)^2} \), but one gets different results depending on whether \( ZW^{-1} \) lies in \( \mathbb{D}^+ \) or \( \mathbb{D}^- \):

**Proposition 10** (Proposition 27, [FL1]). We have the following matrix coefficient expansions

\[
\frac{1}{N(Z-W)^2} = \sum_{k,l,m,n} (2l + 1) t_{m,n}^l (Z^{-1}) \cdot N(Z)^{-k-2} \cdot t_{m,n}^l (W) \cdot N(W)^k
\]

which converges pointwise absolutely in the region \( \{(Z,W) \in \mathbb{H}_\mathbb{C} \times \mathbb{H}_\mathbb{C}; ZW^{-1} \in \mathbb{D}^+\} \), and

\[
\frac{1}{N(Z-W)^2} = \sum_{k,l,m,n} (2l + 1) t_{m,n}^l (Z) \cdot N(Z)^k \cdot t_{m,n}^l (W^{-1}) \cdot N(W^{-1})^{-k-2}
\]

which converges pointwise absolutely in the region \( \{(Z,W) \in \mathbb{H}_\mathbb{C} \times \mathbb{H}_\mathbb{C}; ZW^{-1} \in \mathbb{D}^+\} \). The sums are taken first over all \( m, n = -l, -l+1, \ldots, l \), then over \( k = 0, 1, 2, 3, \ldots \) and \( l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots \).
In this section we formally compute the reproducing kernel for \((\rho_1, \mathcal{K}^0)\). There are some issues with convergence that require justification, but it is nice to see that this formally computed kernel agrees with the formula for a projector onto \(\mathcal{K}^0\) that will be obtained in the next section (Theorem 15).

Recall that \(\mathcal{K}^0\) is the \(\mathbb{C}\)-span of \(\{t_{nm}^{l}(Z) \cdot N(Z)^{k}; -(2l + 1) \leq k \leq -1\}\). In light of the orthogonality relations (19) we would like to compute the series

\[
\sum_{k,l,m,n} (2l + 1)t_{nm}^{l}(Z^{-1}) \cdot N(Z)^{-k-2} \cdot t_{mn}^{l}(W) \cdot N(W)^{k};
\]

the sum is being taken over all \(l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots\), \(m, n \in \mathbb{Z} + l\) with \(m, n = -l, -l + 1, \ldots, l\) and \(-(2l + 1) \leq k \leq -1\). By the multiplicativity property of matrix coefficients (15), (32) equals

\[
\sum_{k,l,m,n} 2l + 1 = \frac{t_{nm}^{l}(Z^{-1}W) \cdot N(Z^{-1}W)^{k}}{N(Z)^{2} \cdot t_{ln}^{l}(Z^{-1}W) \cdot N(Z^{-1}W)^{k}} = \sum_{l,n} 2l + 1 \frac{N(Z^{-1}W)^{-(2l + 1)} - 1}{1 - N(Z^{-1}W)}.
\]

Assume further that \(Z^{-1}W\) can be diagonalized as \((\begin{smallmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{smallmatrix})\) with \(\lambda_1 \neq \lambda_2\). This is allowed since the set of matrices with different eigenvalues is dense in \(\mathbb{H}_{\mathbb{C}}\). Then the sum \(\sum_{l} t_{nm}^{l}(Z^{-1}W)\) is just the character \(\chi(Z^{-1}W)\) of the irreducible representation of \(GL(2, \mathbb{C})\) of dimension \(2l + 1\) and equals \(\lambda^{2l+1}_{1} - \lambda^{2l+1}_{2}\). Hence (32) is equal to

\[
\sum_{l} 2l + 1 = \frac{\lambda^{2l+1}_{1} - \lambda^{2l+1}_{2}}{\lambda_1 - \lambda_2} \cdot \frac{(\lambda_1 \lambda_2)^{-(2l + 1)} - 1}{1 - \lambda_1 \lambda_2} - \sum_{l} 2l + 1 \frac{\lambda^{2l+1}_{1} - \lambda^{2l+1}_{2}}{\lambda_1 - \lambda_2} \cdot \frac{(\lambda_1 - \lambda_2)(1 - \lambda_1 \lambda_2)}{(1 - \lambda_1 \lambda_2)}.
\]

The first sum converges absolutely if \(|\lambda_1| < 1\) and \(|\lambda_2| > 1\):

\[
\sum_{l} 2l + 1 = \frac{\lambda^{2l+1}_{1} - \lambda^{2l+1}_{2}}{(\lambda_1 - \lambda_2)(1 - \lambda_1 \lambda_2)} \cdot \frac{N(Z)^{-2}}{(1 - \lambda_1 \lambda_2)^{2}(1 - \lambda_2)2} = \frac{N(Z)^{-2}}{N(1 - Z^{-1}W)^{2}} = \frac{1}{N(Z - W)^{2}}.
\]

The second sum converges absolutely if \(|\lambda_1| > 1\) and \(|\lambda_2| < 1\):

\[
\sum_{l} 2l + 1 = \frac{\lambda^{2l+1}_{1} - \lambda^{2l+1}_{2}}{(\lambda_1 - \lambda_2)(1 - \lambda_1 \lambda_2)} = \frac{1}{N(Z - W)^{2}}.
\]

Of course, the set of \(Z\) and \(W\) where both sums converge absolutely is empty, but these formal calculations strongly suggest that there is a way to make sense of the series (32) in terms of distributions:

\[
\sum_{k,l,m,n} (2l + 1)t_{nm}^{l}(Z^{-1}) \cdot N(Z)^{-k-2} \cdot t_{mn}^{l}(W) \cdot N(W)^{k} = -\left(\text{Reg}+ \frac{1}{N(Z-W)^{2}} + \text{Reg}^{-} \frac{1}{N(Z-W)^{2}}\right)
\]

with \(ZW^{-1} \in U(2)\) and \(\text{Reg}^{\pm} \frac{1}{N(Z-W)^{2}}\) denoting some sort of regularizations of \(\frac{1}{N(Z-W)^{2}}\).
6 Equivariant Embeddings of and Projectors onto the Irreducible Components of \((\rho_1, \mathcal{K})\)

In this section we construct \(\mathfrak{gl}(2, \mathbb{H}_C)\)-equivariant embeddings of the irreducible components of \((\rho_1, \mathcal{K})\) into tensor products \((\pi^0_1, \mathcal{H}^+) \otimes (\pi^0_1, \mathcal{H}^+)\) with the property that, when composed with the multiplication map, the result is the identity map on that irreducible component. The tensor product \((\pi^0_1, \mathcal{H}^+) \otimes (\pi^0_1, \mathcal{H}^+)\) was decomposed into a direct sum of irreducible components in [JV] with \((\rho_1, \mathcal{K}^+)\) being one of these components, and it was shown that each irreducible component has multiplicity one. Hence the \(\mathfrak{gl}(2, \mathbb{H}_C)\)-equivariant map \(\mathcal{K}^+ \to \mathcal{H}^+ \otimes \mathcal{H}^+\) is unique up to a scalar multiple. Dually, the multiplicity of \((\rho_1, \mathcal{K}^-)\) in \((\pi^0_1, \mathcal{H}^-) \otimes (\pi^0_1, \mathcal{H}^-)\) is one and the \(\mathfrak{gl}(2, \mathbb{H}_C)\)-equivariant map \(\mathcal{K}^- \to \mathcal{H}^- \otimes \mathcal{H}^-\) is unique up to a scalar multiple as well. On the other hand, the equivariant embedding \(\mathcal{K}^0 \to \mathcal{H}^- \otimes \mathcal{H}^+\) requires a more subtle approach. As an immediate application of these embedding maps we obtain projectors of \((\rho_1, \mathcal{K})\) onto its irreducible components.

We consider the maps

\[
\mathcal{K} \ni f \mapsto (I_R f)(Z_1, Z_2) = \frac{i}{2\pi^3} \int_{W \in U(2)_R} \frac{f(W) \, dV}{N(W - Z_1) \cdot N(W - Z_2)} \in \mathcal{H} \otimes \mathcal{H},
\]

where \(\mathcal{H} \otimes \mathcal{H}\) denotes the Hilbert space obtained by completing \(\mathcal{H} \otimes \mathcal{H}\) with respect to the unitary structure coming from the tensor product of unitary representations \((\pi^0_1, \mathcal{H})\) and \((\pi^0_1, \mathcal{H})\). If \(Z_1, Z_2 \in \mathbb{D}_R^- \cup \mathbb{D}_R^+\), the integrand has no singularities and the result is a holomorphic function in two variables \(Z_1, Z_2\) which is harmonic in each variable separately. We will see soon that the result depends on whether \(Z_1\) and \(Z_2\) are both in \(\mathbb{D}_R^+\), both in \(\mathbb{D}_R^-\) or one is in \(\mathbb{D}_R^+\) and the other is in \(\mathbb{D}_R^-\). Thus the expression (34) determines four different maps.

**Lemma 11.** The maps \(f \mapsto (I_R f)(Z_1, Z_2)\) are \(U(2, 2)_R\) and \(\mathfrak{gl}(2, \mathbb{H}_C)\)-equivariant.

**Proof.** We need to show that, for all \(h \in U(2, 2)_R\), the maps (34) commute with the action of \(h\). Writing \(h = (a' b' \ c' \ d'), h^{-1} = (a \ b \ c \ d)\),

\[
\tilde{Z}_1 = (aZ_1 + b)(cZ_1 + d)^{-1}, \quad \tilde{Z}_2 = (aZ_2 + b)(cZ_2 + d)^{-1}, \quad \tilde{W} = (aW + b)(cW + d)^{-1}
\]

and using Lemmas 1 and 2 we obtain:

\[
\int_{W \in U(2)_R} \frac{(\rho_1(h)f)(W) \, dV}{N(W - Z_1) \cdot N(W - Z_2)} = \int_{W \in U(2)_R} \frac{f(\tilde{W}) \cdot N(cW + d)^{-2} \cdot N(a' - Wc')^{-2} \, dV}{N(W - \tilde{Z}_1) \cdot N(W - \tilde{Z}_2) \cdot N(cZ_1 + d) \cdot N(a' - Z_2c')} = \frac{1}{N(cZ_1 + d) \cdot N(a' - Z_2c')} \int_{W \in U(2)_R} \frac{f(\tilde{W}) \, dV}{N(W - \tilde{Z}_1) \cdot N(W - \tilde{Z}_2)}.
\]

This proves the \(U(2, 2)_R\)-equivariance. The \(\mathfrak{gl}(2, \mathbb{H}_C)\)-equivariance then follows since \(\mathfrak{gl}(2, \mathbb{H}_C) \simeq \mathbb{C} \otimes \mathfrak{u}(2, 2)_R\). \(\square\)

Now we compose the embedding maps \(I_R\) with the multiplication map \(M\) defined by (29).

**Theorem 12.** The maps \(f \mapsto (I_R f)(Z_1, Z_2)\) have the following properties:

1. If \(Z_1, Z_2 \in \mathbb{D}_R^+\), then \(I_R : \mathcal{K} \to \mathcal{H}^+ \otimes \mathcal{H}^+\),

\[
M \circ (I_R f)(Z_1, Z_2) = f \quad \text{if} \quad f \in \mathcal{K}^+ \quad \text{and} \quad (I_R f)(Z_1, Z_2) = 0 \quad \text{if} \quad f \in \mathcal{K}^- \oplus \mathcal{K}^0;
\]

2. If \(Z_1, Z_2 \in \mathbb{D}_R^-\), then \(I_R : \mathcal{K} \to \mathcal{H}^- \otimes \mathcal{H}^-\),

\[
M \circ (I_R f)(Z_1, Z_2) = f \quad \text{if} \quad f \in \mathcal{K}^- \quad \text{and} \quad (I_R f)(Z_1, Z_2) = 0 \quad \text{if} \quad f \in \mathcal{K}^+ \oplus \mathcal{K}^0;
\]

3. If \(Z_1, Z_2 \in \mathbb{D}_R^+ \cup \mathbb{D}_R^-\), then \(I_R : \mathcal{K} \to \mathcal{H}^+ \oplus \mathcal{H}^-\),

\[
M \circ (I_R f)(Z_1, Z_2) = f \quad \text{if} \quad f \in \mathcal{K}^+ \oplus \mathcal{K}^- \quad \text{and} \quad (I_R f)(Z_1, Z_2) = 0 \quad \text{if} \quad f \in \mathcal{K}^0;
\]
2. If $Z_1, Z_2 \in \mathbb{D}_R^-$, then $I_R : \mathcal{K} \to \mathcal{H}^- \otimes \mathcal{H}^-$, 

$$M \circ (I_R f)(Z_1, Z_2) = f \quad \text{if} \quad f \in \mathcal{K}^- \quad \text{and} \quad (I_R f)(Z_1, Z_2) = 0 \quad \text{if} \quad f \in \mathcal{K}^0 \oplus \mathcal{K}^+.$$ 

**Proof.** We prove part 1 only, the other part can be proven in the same way. Note that the representations $(\rho_1, \mathcal{K}^-)$, $(\rho_1, \mathcal{K}^0)$ and $(\rho_1, \mathcal{K}^+)$ are generated by $N(W)^{-2}$, $N(W)^{-1}$ and 1 respectively. For this reason we compute $(I_R N(W)^k)(Z_1, Z_2)$ for $k = -2, -1, 0$. Suppose $Z_1, Z_2 \in \mathbb{D}_R^+$ and use the matrix coefficient expansion given by Proposition 25 in [FL1]

$$\frac{1}{N(Z - W)} = N(W)^{-1} \cdot \sum_{l,m,n} t^l_{m,n}(Z) \cdot t^l_{m,n}(W^{-1}), \quad l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots, m, n = -l, -l + 1, \ldots, l, \quad (35)$$

which converges pointwise absolutely in the region $\{(Z, W) \in \mathbb{H}_{\mathbb{C}} \times \mathbb{H}_{\mathbb{C}}^2; Z W^{-1} \in \mathbb{D}^+\}$. We compute:

$$(I_R N(W)^k)(Z_1, Z_2) = \frac{i}{2\pi^3} \int_{W \in U(2)R} \frac{N(W)^k dV}{N(W - Z_1) \cdot N(W - Z_2)} = \left< \frac{N(W)^k}{N(W - Z_1)}, \frac{1}{N(W + Z_2^+)} \right>_W = \sum_{l,m,n,l',m'} t^l_{m,n}(Z_1) \cdot t^{l'}_{m',n'}(Z_2^+). \langle N(W)^{k-2} \cdot t^l_{m,n}(W^{-1}), t^{l'}_{m',n'}(W) \rangle.$$ 

By the orthogonality relations (19) this is zero unless $l = l'$, $m = m'$, $n = n'$ and $k = 2l$. Therefore,

$$(I_R N(W)^k)(Z_1, Z_2) = \begin{cases} 0 & \text{if} \quad k = -2, -1; \\ 1 & \text{if} \quad k = 0. \end{cases}$$ 

By $\mathfrak{gl}(2, \mathbb{H}_{\mathbb{C}})$-equivariance (Lemma 11) we see that $(I_R f)(Z_1, Z_2)$ is always a polynomial in $Z_1$ and $Z_2$, hence an element of $\mathcal{H}^+ \otimes \mathcal{H}^+$ and part 1 follows. \(\square\)

**Example 13.** Using similar computations one can show that

$$(I_R N(W))(Z_1, Z_2) = \frac{1}{2} \text{Tr}(Z_1 Z_2^+) \quad \text{and} \quad (I_R w_{ij})(Z_1, Z_2) = \frac{1}{2} ((z_{ij})_1 + (z_{ij})_2), \quad Z_1, Z_2 \in \mathbb{D}_R^+,$$

where $w_{ij}$ denotes the $ij$-entry of the $2 \times 2$ matrix $W$.

**Corollary 14.** The maps $f \mapsto (I_R f)(Z_1, Z_2)$ followed by the multiplication map provide projectors onto the irreducible components of $(\rho_1, \mathcal{K})$. More precisely,

1. If $Z \in \mathbb{D}_R^+$, then the map

$$f \mapsto (P^+ f)(Z) = \frac{i}{2\pi^3} \int_{W \in U(2)R} \frac{f(W) dV}{N(W - Z)^2}$$

is a projector onto $\mathcal{K}^+$;

2. If $Z \in \mathbb{D}_R^-$, then the map

$$f \mapsto (P^- f)(Z) = \frac{i}{2\pi^3} \int_{W \in U(2)R} \frac{f(W) dV}{N(W - Z)^2}$$

is a projector onto $\mathcal{K}^-$.
In particular, these maps $P^+$ and $P^-$ provide reproducing formulas for functions in $K^+$ and $K^\ast$ respectively.

(The reproducing formula for functions in $K^+$ was obtained in [FL1], Theorem 70.)

Now we suppose $Z_1 \in \mathbb{D}_R^+$ and $Z_2 \in \mathbb{D}_R^+$, this case is much more subtle. Using the matrix coefficient expansion (35) of $N(Z - W)^{-1}$ one more time, we compute:

$$(I_R N(W)^k)(Z_1, Z_2) = \frac{i}{2\pi^3} \int_{W \in U(2)_R} \frac{N(W)^k}{N(W - Z_1) \cdot N(W - Z_2)} dV = \left\langle \frac{N(W)^k}{N(W - Z_1)^{-1} \cdot N(W - Z_2)} \right\rangle_W = N(Z_2)^{-1} \sum_{l,m,n,l',m',n'} t^l_{m,n}(Z_1) \cdot t^{l'}_{m',n'}(Z_2^{-1}) \cdot \langle N(W)^k \cdot t^l_{m,n}(W^{-1} \cdot t^{l'}_{m,n}(W)).$$

By the orthogonality relations (19) this is zero unless $l = l'$, $m = m'$, $n = n'$ and $k = -1$. By $gl(2, \mathbb{H}_C)$-equivariance (Lemma 11) we can conclude that $(I_R f)(Z_1, Z_2) = 0$ if $f \in K^\ast \oplus K^\ast$.

So, let us assume now $l = l'$, $m = m'$, $n = n'$ and $k = -1$. In this case we get

$$(I_R N(W)^{-1})(Z_1, Z_2) = \sum_{l,m,n} \frac{N(Z_2)^{-1}}{2l + 1} t^l_{m,n}(Z_1) \cdot t^{l'}_{m',n'}(Z_2^{-1}) = \sum_{l,n} \frac{N(Z_2)^{-1}}{2l + 1} t_{n'(Z_1)} \cdot t^{l'}_{m',n'}(Z_2^{-1}).$$

Assume further that $Z_1 \cdot Z_2^{-1}$ can be diagonalized as $(\lambda_1, 0 \lambda_2)$ with $\lambda_1 \neq \lambda_2$. This is allowed since the set of matrices with different eigenvalues is dense in $\mathbb{H}_C$. Since $Z_1 \in \mathbb{D}_R^+$ and $Z_2 \in \mathbb{D}_R^+$, we have $|\lambda_1|, |\lambda_2| < 1$. Recall that $\chi_l$ denotes the character of the irreducible representation of $GL(2, \mathbb{C})$ of dimension $2l + 1$ and $\chi_l(Z_1 \cdot Z_2^{-1}) = \frac{\lambda_1^{2l+1} - \lambda_2^{2l+1}}{\lambda_1 - \lambda_2}$. Hence

$$(I_R N(W)^{-1})(Z_1, Z_2) = \sum_l \frac{N(Z_2)^{-1}}{2l + 1} \chi_l(Z_1 \cdot Z_2^{-1}) = \sum_l \frac{N(Z_2)^{-1}}{2l + 1} \chi_l(Z_1 \cdot Z_2^{-1}) = \frac{N(Z_2)^{-1}}{\chi_l(Z_1 \cdot Z_2^{-1})} \log \left( 1 - \frac{1}{2l + 1} \right).$$

Although this expression is valid only in the region where $\lambda_1 \neq \lambda_2$, the right hand side clearly continues analytically across the set of $Z_1 \cdot Z_2^{-1}$ for which $\lambda_1 = \lambda_2$. However, this is obviously not a polynomial in $Z_1, Z_2, N(Z_1)^{-1}, N(Z_2)^{-1}$ and hence not an element of $\mathcal{H} \otimes \mathcal{H}$. Note that composing $(I_R N(W)^{-1})(Z_1, Z_2)$ with the multiplication map $M$ amounts to setting $Z_1 = Z_2 = Z$ and letting $\lambda_1, \lambda_2 \to 1$, but then the limit is infinite! To get around this problem, observe that (36) remains valid if we let $Z_1$ and $Z_2$ approach two different points in $U(2)_R$ so that $Z_1 \in \mathbb{D}_R^+$ and $Z_2 \in \mathbb{D}_R^+$. Thus we have a well defined operator

$$f \mapsto (I_R^- f)(Z_1, Z_2) = \frac{i}{2\pi^3} \lim_{Z_1' \to Z_1, Z_1' \in \mathbb{D}_R^+} \int_{W \in U(2)_R} \frac{f(W) \cdot dV}{N(W - Z_1') \cdot N(W - Z_2')}.$$
where \( Z_1, Z_2 \in U(2)_R \) and \( N(Z_1 - Z_2) \neq 0 \).

It follows from Lemma 11 that the operators \( I_R^+ \) and \( I_R^- \) are \( U(2, 2)_R \)-equivariant. We already know that these operators annihilate \( N(Z) \) for \( k \neq -1 \). Hence they annihilate the entire \( \mathcal{H}^- \oplus \mathcal{H}^+ \). Next we compute the limit

\[
\lim_{Z_1, Z_2 \to Z} ((I_R^+ + I_R^-)N(W)^{-1})(Z_1, Z_2), \quad Z \in U(2)_R.
\]

As before, suppose that \( Z_1 \cdot Z_2^{-1} \) has eigenvalues \( \lambda_1 \) and \( \lambda_2 \) with \( |\lambda_1| = |\lambda_2| = 1 \), \( \lambda_1 \neq 1 \) and \( \lambda_2 \neq 1 \). Then \( N(Z_1) = \lambda_1 \lambda_2 \cdot N(Z_2) \), \( Z_2 \cdot Z_1^{-1} \) has eigenvalues \( \lambda_1^{-1} \) and \( \lambda_2^{-1} \). Assume for a moment that \( \lambda_1 \neq \lambda_2 \), then by (36) we have:

\[
((I_R^+ + I_R^-)N(W)^{-1})(Z_1, Z_2) = \frac{N(Z_2)^{-1}}{\lambda_2 - \lambda_1} \log \left( \frac{1 - \lambda_1}{1 - \lambda_2} \right) - \frac{N(Z_2)^{-1}}{\lambda_2 - \lambda_1} \log \left( \frac{\lambda_2 (\lambda_1 - 1)}{\lambda_1 (\lambda_2 - 1)} \right) = -\frac{1}{N(Z_2)} \log \frac{\lambda_2 - \lambda_1}{\lambda_1 - \lambda_2}.
\]

Hence,

\[
((I_R^+ + I_R^-)N(W)^{-1})(Z_1, Z_2) = -\frac{1}{N(Z_2)} \begin{cases} \log \frac{\lambda_2 - \lambda_1}{\lambda_1 - \lambda_2}, & \text{if } \lambda_1 \neq \lambda_2; \\ \lambda_1^{-1}, & \text{if } \lambda_1 = \lambda_2 = \lambda. \end{cases}
\]

Therefore,

\[
\lim_{Z_1, Z_2 \to Z, \lambda_1 \neq \lambda_2} ((I_R^+ + I_R^-)N(W)^{-1})(Z_1, Z_2) = -N(Z)^{-1}, \quad Z \in U(2)_R.
\]

From the \( U(2, 2)_R \)-equivariance we see that we have obtained a projector onto \( \mathcal{H}^0 \):

**Theorem 15.** The \( \mathfrak{gl}(2, \mathbb{H}_C) \)-equivariant map

\[
f \mapsto (I_R^+ + I_R^-)f)(Z_1, Z_2) \in \mathcal{H} \otimes \mathcal{H}, \quad f \in \mathcal{H}, \quad Z_1, Z_2 \in U(2)_R,
\]

is well-defined, annihilates \( \mathcal{H}^- \oplus \mathcal{H}^+ \) and satisfies

\[
M \circ ((I_R^+ + I_R^-)f) = f \quad \text{if } f \in \mathcal{H}^0.
\]

In particular, an operator \( P^0 \) on \( \mathcal{H} \)

\[
f \mapsto (P^0 f)(Z) = \lim_{Z_1, Z_2 \to Z, \lambda_1 \neq \lambda_2} ((I_R^+ + I_R^-)f)(Z_1, Z_2), \quad Z \in U(2)_R,
\]

is well-defined, annihilates \( \mathcal{H}^- \oplus \mathcal{H}^+ \) and is the identity mapping on \( \mathcal{H}^0 \).

Finally, the operator \( P^0 \) on \( \mathcal{H} \) can be computed as follows:

\[
(P^0 f)(Z) = \frac{1}{2\pi i} \lim_{\theta \to 0} \lim_{s \to 1} \left( \int_{W \in U(2)_R} \frac{f(W) \, dV}{N(W - s e^{i\theta} Z) \cdot N(W - s^{-1} e^{-i\theta} Z)} + \int_{W \in U(2)_R} \frac{f(W) \, dV}{N(W - s^{-1} e^{i\theta} Z) \cdot N(W - s e^{-i\theta} Z)} \right), \quad Z \in U(2)_R.
\]

Note that the space \( \mathcal{H} \) consists of rational functions, and rational functions on \( \mathbb{H}_C \) as well as analytic ones are completely determined by their values on \( U(2)_R \). Note also that this integral formula for \( P^0 \) is in complete agreement with our previous formal computation (33) of the reproducing kernel for \( (\rho_1, \mathcal{H}^0) \).

**Remark 16.** Every function \( f \in \mathcal{H} \) can be written as \( f = P^- f + P^0 f + P^+ f \). Combining the integral expressions for \( P^\pm f \) and \( P^0 f \) obtained in Corollary 14 and Theorem 15 we get a reproducing formula for all functions in \( \mathcal{H} \) that is equivalent to (9).
7 The One-Loop Feynman Integral and Its Relation to 
\((\pi_1^0, H^\pm) \otimes (\pi_2^0, H^\pm)\)

In this section we show that the identification of the one-loop Feynman diagram with the integral 
kernel \(1(Z_1, Z_2; W_1, W_2)\) of the integral operators expressing \(\mathcal{P}^+\) and \(\mathcal{P}^-\) found in [FL1] is 
an immediate consequence of Theorem 12. These operators \(\mathcal{P}^+\) and \(\mathcal{P}^-\) are the \(\frak{gl}(2, \mathbb{H}_C)\)-
equivariant composition maps

\[
\mathcal{P}^+: H^+ \otimes H^+ \to \mathcal{K}^+ \hookrightarrow H^+ \otimes H^+ \quad \text{and} \quad \mathcal{P}^-: H^- \otimes H^- \to \mathcal{K}^- \hookrightarrow H^- \otimes H^- \quad (37)
\]

(the multiplication map followed by the embedding). As we mentioned earlier, the multiplicities 
of \((\rho_1, \mathcal{K}^+)\) in \((\pi_1^0, H^+) \otimes (\pi_2^0, H^+)\) and of \((\rho_1, \mathcal{K}^-)\) in \((\pi_1^0, H^-) \otimes (\pi_2^0, H^-)\) are both one. So the maps \(\mathcal{P}^+\) and \(\mathcal{P}^-\) are unique up to multiplication by scalars and they are pinned down by imposing

\[
\mathcal{P}^+(1 \otimes 1) = 1 \otimes 1 \quad \text{and} \quad \mathcal{P}^- (N(Z_1)^{-1} \otimes N(Z_2)^{-1}) = N(W_1)^{-1} \otimes N(W_2)^{-1}.
\]

For convenience we restate Theorem 34 and Corollary 39 from [FL1]. We define operators 
on \(\mathcal{H}\) by

\[
(S_R^+ \varphi)(Z) = \frac{1}{2\pi^2} \int_{X \in S^3_R} \frac{(d\varphi)(X)}{N(X - Z)} \frac{dS}{R}, \quad Z \in \mathbb{D}_R^+,
\]

\[
(S_R^- \varphi)(Z) = \frac{1}{2\pi^2} \int_{X \in S^3_R} \frac{(d\varphi)(X)}{N(X - Z)} \frac{dS}{R}, \quad Z \in \mathbb{D}_R^-.
\]

**Theorem 17.** The operators \(S_R^+\) and \(S_R^-\) are continuous linear operators \(\mathcal{H} \to \mathcal{H}\). The operator 
\(S_R^+\) has image in \(\mathcal{H}^+\) and sends

\[
t_{m,n}^l(X) \mapsto t_{m,n}^l(Z), \quad l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots,
\]

\[
t_{m,n}^l(X) \cdot N(X)^{-2l-1} \mapsto -R^{-2(2l+1)} \cdot t_{m,n}^l(Z), \quad -l \leq m, n \leq l.
\]

The operator \(S_R^-\) has image in \(\mathcal{H}^-\) and sends

\[
t_{m,n}^l(X) \mapsto R^{2(2l+1)} \cdot N(Z)^{-2l-1} \cdot t_{m,n}^l(Z), \quad l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots,
\]

\[
t_{m,n}^l(X) \cdot N(X)^{-2l-1} \mapsto -t_{m,n}^l(Z) \cdot N(Z)^{-2l-1}, \quad -l \leq m, n \leq l.
\]

Now, let us take a close look at the function of three variables

\[
\frac{1}{N(W - Z_1) \cdot N(W - Z_2)}.
\]

On the one hand, this function has appeared in (34) and is responsible for \(\frak{gl}(2, \mathbb{H}_C)\)-equivariant embeddings of \(\mathcal{K}^\pm\) into \(\mathcal{H}^+ \otimes \mathcal{H}^\pm\). On the other hand, as can be seen from Theorem 17, this function can be used to express the multiplication maps (29):

**Lemma 18.** Fix \(R_1, R_2 > 0\) and consider a map \(\widetilde{M}\) on \(\mathcal{H} \otimes \mathcal{H}\) sending pure tensors

\[
\varphi_1(Z_1) \otimes \varphi_2(Z_2) \mapsto \frac{1}{(2\pi^2)^2} \int_{Z_1 \in S^3_{R_1}} \int_{Z_2 \in S^3_{R_2}} \frac{(d\varphi_1)(Z_1) \cdot (d\varphi_2)(Z_2)}{N(W - Z_1) \cdot N(W - Z_2)} \cdot \frac{dS_1 \, dS_2}{R_1 R_2}.
\]
8 Minkowski Space Realization of $\mathcal{K}^-, \mathcal{K}^0$ and $\mathcal{K}^+$

In this section we realize the spaces $\mathcal{K}^-, \mathcal{K}^0$ and $\mathcal{K}^+$ in the setting of the Minkowski space $\mathcal{M}$. As in [FL1], we use $e_0, e_1, e_2, e_3$ in place of the more familiar generators $1, i, j, k$ of $\mathbb{H}$, so that the symbol $i$ can be used for $\sqrt{-1} \in \mathbb{C}$; and let $\tilde{e}_0 = -i e_0 \in \mathbb{H}_\mathbb{C}$. Then

$$\mathcal{M} = \tilde{e}_0 \mathbb{R} \oplus e_1 \mathbb{R} \oplus e_2 \mathbb{R} \oplus e_3 \mathbb{R} = \left\{ \begin{array}{l} \mathbb{Z} = \begin{pmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{pmatrix} \in \mathbb{H}_\mathbb{C}; \ z_{11}, z_{22} \in \mathbb{R}, \ z_{21} = -\bar{z}_{12} \end{array} \right\}. $$

Figure 4: One-loop Feynman diagram
Recall the generalized upper and lower half-planes introduced in Section 3.5 in [FL1]:

\[ T^- = \{ Z = W_1 + iW_2 \in \mathbb{H}_\mathbb{C} ; W_1, W_2 \in \mathbb{M}, iW_2 \text{ is positive definite} \}, \]

\[ T^+ = \{ Z = W_1 + iW_2 \in \mathbb{H}_\mathbb{C} ; W_1, W_2 \in \mathbb{M}, iW_2 \text{ is negative definite} \} \]

and element \( \gamma \in GL(2, \mathbb{C}) \) from Lemmas 54 and 63 of [FL1] which induces a fractional linear transformation on \( \mathbb{H}_\mathbb{C} \) that we call the “Cayley transform”. Thus \( \gamma = \frac{1}{\sqrt{2}} \left( \begin{array}{cc} 1 & i \\ i & -1 \end{array} \right) \in GL(2, \mathbb{H}_\mathbb{C}) \) with \( \gamma^{-1} = \frac{1}{\sqrt{2}} \left( \begin{array}{cc} 1 & i \\ -i & 1 \end{array} \right) \). The fractional linear map on \( \mathbb{H}_\mathbb{C} \)

\[ \pi_l(\gamma) : Z \mapsto (Z - i)(Z + i)^{-1} \]

maps \( \mathbb{D}^+ \to T^+, \mathbb{D}^- \to T^-, U(2) \to M \) (with singularities) and sends the sphere \( \{ Z \in U(2); N(Z) = 1 \} = SU(2) \) into the two-sheeted hyperboloid \( \{ Y \in M; N(Y) = -1 \} \). Conversely, the fractional linear map on \( \mathbb{H}_\mathbb{C} \)

\[ \pi_l(\gamma^{-1}) : Z \mapsto -i(Z + 1)(Z - 1)^{-1} \]

maps \( T^+ \to \mathbb{D}^+, T^- \to \mathbb{D}^-, M \to U(2) \), has no singularities on \( M \), and sends the two-sheeted hyperboloid \( \{ Y \in M; N(Y) = -1 \} \) into the sphere \( \{ Z \in U(2); N(Z) = 1 \} = SU(2) \).

These fractional linear transformations induce the following maps on functions:

\[ \pi_l^0(\gamma) : \varphi(Z) \mapsto (\pi_l^0(\gamma)\varphi)(Z) = \frac{2}{N(Z+1)} \cdot \varphi(-i(Z + 1)(Z - 1)^{-1}), \]

sends harmonic functions\(^2\) on \( \mathbb{D}^+, \mathbb{D}^- \) and \( U(2) \) into solutions of the wave equation on, respectively, \( T^+, T^- \) and \( M \). Similarly,

\[ \pi_l^0(\gamma^{-1}) : \varphi(Z) \mapsto (\pi_l^0(\gamma^{-1})\varphi)(Z) = \frac{-2}{N(Z + i)} \cdot \varphi((Z - i)(Z + i)^{-1}), \]

sends solutions of the wave equation on \( T^+, T^- \) and \( M \) into harmonic functions on, respectively, \( \mathbb{D}^+, \mathbb{D}^- \) and \( U(2) \). In particular, \( \pi_l^0(\gamma) \) maps

\[ 1 \mapsto 2 \cdot N(Z - 1)^{-1}, \quad N(Z)^{-1} \mapsto -2 \cdot N(Z + 1)^{-1}. \] (38)

The light cone

\[ \text{Cone} = \{ Y \in M; N(Y) = 0 \} \]

can be divided into two parts:

\[ \text{Cone}^+ = \{ Y \in \text{Cone}; i \text{ Tr } Y \geq 0 \} \quad \text{and} \quad \text{Cone}^- = \{ Y \in \text{Cone}; i \text{ Tr } Y \leq 0 \}. \]

Next we calculate the (inverse) Fourier transform of the delta distributions on \( \text{Cone}^+ \) and \( \text{Cone}^- \):

**Lemma 19.** We have the following absolutely convergent expansions:

\[ \frac{1}{N(Z)} = \frac{1}{4\pi} \int_{P \in \text{Cone}^+} e^{i(Z,P)} \frac{dp^1 dp^2 dp^3}{|p^0|}, \quad Z \in T^+, \]

\[ \frac{1}{N(Z)} = \frac{1}{4\pi} \int_{P \in \text{Cone}^-} e^{i(Z,P)} \frac{dp^1 dp^2 dp^3}{|p^0|}, \quad Z \in T^-, \]

where \( \langle Z, P \rangle = \text{Tr}(Z^+P)/2 = \text{Tr}(P^+Z)/2 \) and \( P = p^0 e_0 + p^1 e_1 + p^2 e_2 + p^3 e_3 \in \text{Cone}^{\pm} \subset M. \)

\(^2\)By harmonic functions on \( U(2) \) we mean functions that are holomorphic and harmonic in some open neighborhood of \( U(2) \).
Proof. Note that \( iW \in i\mathbb{M} \) is positive definite if and only if \( N(W) < 0 \) and \( i\text{Tr} W > 0 \) or, equivalently, if and only if \( W = w^0 \tilde{e}_0 + w^1 e_1 + w^2 e_2 + w^3 e_3 \in \mathbb{M} \) and \( w^0 > |\tilde{w}| = (w^1)^2 + (w^2)^2 + (w^3)^2 \). Similarly, \( iW \in i\mathbb{M} \) is negative definite if and only if \( W = w^0 \tilde{e}_0 + w^1 e_1 + w^2 e_2 + w^3 e_3 \in \mathbb{M} \) and \( w^0 < |\tilde{w}| \). This implies that the two integrals converge absolutely on the respective regions.

Each integral defines a complex analytic function of \( Z \) on \( \mathbb{T}^- \) and \( \mathbb{T}^+ \) respectively. Hence to establish that the integrals are equal to \( N(Z)^{-1} \), it is sufficient to prove that for \( Z \) of the form \( z^0 \tilde{e}_0 + z^1 e_1 + z^2 e_2 + z^3 e_3 \in \mathbb{H}_C \) with \( z^0 \in \mathbb{C}^* \) and \( \mathbb{P} = (z^1, z^2, z^3) \in \mathbb{R}^3 \). Rotating \( Z \) if necessary, without loss of generality we can assume that \( z^2 = z^3 = 0 \). For \( \mathbb{P} = (p^1, p^2, p^3) \in \mathbb{R}^3 \), let

\[
\begin{align*}
P_+ = |\mathbb{P}| \tilde{e}_0 + p^1 e_1 + p^2 e_2 + p^3 e_3 & \in \text{Cone}^+, \\
P_- = -|\mathbb{P}| \tilde{e}_0 + p^1 e_1 + p^2 e_2 + p^3 e_3 & \in \text{Cone}^-.
\end{align*}
\]

Let \( s = (p^2)^2 + (p^3)^2 \) and substitute \( u = (p^1)^2 + s^2 \), then the integrals in question become

\[
\begin{align*}
\int_{P \in \text{Cone}^+} e^{i\langle Z, P \rangle} \frac{dp^1 dp^2 dp^3}{|\mathbb{P}|} &= \int_{\mathbb{P} \in \mathbb{R}^3} \exp(i(z^0 |\mathbb{P}| + z^1 p^1)) \frac{dp^1 dp^2 dp^3}{|\mathbb{P}|} \\
&= 2\pi \int_{s \geq 0} \int_{-\infty < p^1 < \infty} s \exp(i(z^0 \sqrt{(p^1)^2 + s^2} + z^1 p^1)) \frac{dp^1 ds}{\sqrt{(p^1)^2 + s^2}} \\
&= 2\pi \int_{-\infty}^{\infty} \left( \int_{u \geq |\mathbb{P}|} e^{i(z^0 u + z^1 p^1)} du \right) dp^1 \\
&= \pm 2\pi i \int_{-\infty}^{\infty} e^{i(z^0 |\mathbb{P}| + z^1 p^1)} dp^1 = \frac{4\pi}{(z^1)^2 - (z^0)^2} = \frac{4\pi}{N(Z)}.
\end{align*}
\]

Therefore,

\[
\frac{1}{N(Z_1 - Z_2)} = \frac{1}{4\pi} \int_{P \in \text{Cone}^-} e^{i\langle Z_1 - Z_2, P \rangle} \frac{dp^1 dp^2 dp^3}{|\mathbb{P}|}, \quad \text{whenever } Z_1 - Z_2 \in \mathbb{T}^-,
\]

and

\[
\frac{1}{N(Z_1 - Z_2)} = \frac{1}{4\pi} \int_{P \in \text{Cone}^+} e^{i\langle Z_1 - Z_2, P \rangle} \frac{dp^1 dp^2 dp^3}{|\mathbb{P}|}, \quad \text{whenever } Z_1 - Z_2 \in \mathbb{T}^+.
\]

**Corollary 20.** Up to proportionality coefficients, the Fourier transforms of the following distributions on \( \mathbb{M} \) are:

- the FT of \( \frac{1}{N(Y - 1)} \) is the distribution \( f \mapsto \int_{P \in \text{Cone}^+} f(P) \cdot e^{-i\text{Tr} P/2} \frac{dp^1 dp^2 dp^3}{|\mathbb{P}|} \),

- the FT of \( \frac{1}{N(Y + 1)} \) is the distribution \( f \mapsto \int_{P \in \text{Cone}^-} f(P) \cdot e^{i\text{Tr} P/2} \frac{dp^1 dp^2 dp^3}{|\mathbb{P}|} \).

(The presence of the rapidly decaying term \( e^{\pm i\text{Tr} P/2} \) ensures convergence of the integrals.)

Combining this corollary with (38), we see that the Fourier transform maps \( \pi^0_i(\gamma)(\mathcal{H}^+) \) into distributions supported on \( \text{Cone}^+_\gamma \) and \( \pi^1_i(\gamma)(\mathcal{H}^-) \) into distributions supported on \( \text{Cone}^-_\gamma \). Since the Fourier transform maps products of functions into convolutions, by Lemma 8 the Fourier transform maps \( \rho_1(\mathcal{H}^+) \), \( \rho_1(\mathcal{H}^-) \) and \( \rho_1(\mathcal{H}^0) \) into distributions supported respectively in \( \{ Y \in \mathbb{M}; N(Y) < 0, i\text{Tr} Y \geq 0 \} \) – the “interior of \( \text{Cone}^+ \), \( \{ Y \in \mathbb{M}; N(Y) < 0, i\text{Tr} Y \leq 0 \} \) – the “interior of \( \text{Cone}^- \) and \( \{ Y \in \mathbb{M}; N(Y) > 0 \} \) – the “exterior of \( \text{Cone} \).
Next we set \( R = 1 \) and pull back the maps \( I_1 \) defined by (34) via \( \pi_l(\gamma^{-1}) \). Using Lemmas 1 and 2 we obtain a formula that formally looks like (34):

\[
\mathcal{H} \ni f \mapsto (I_1f)(Z_1, Z_2) = \frac{i}{2\pi^3} \int_{Y \in \mathbb{M}} \frac{f(Y) \, dV}{N(Y - Z_1) \cdot N(Y - Z_2)} \in \mathcal{H} \otimes \mathcal{H}.
\]

however, the integration is over \( Y \in \mathbb{M} \), the two copies of \( \mathcal{H} \) are realized as solutions of the wave equation on \( \mathbb{M} \) and \( Z_1, Z_2 \in \mathbb{T}^- \cup \mathbb{T}^+ \). Setting \( Z_1 = Z_2 \in \mathbb{T}^- \) and \( Z_1 = Z_2 \in \mathbb{T}^+ \) results in projectors of \( \rho_1(\mathcal{H}) \) onto \( \rho_1(\mathcal{H}^-) \) and \( \rho_1(\mathcal{H}^+) \) respectively.

**Theorem 21.** Let \( f \in \rho_1(\mathcal{H}) \). If \( Z \in \mathbb{T}^+ \), then the map

\[
f \mapsto P_M^+(Z) = \frac{i}{2\pi^3} \int_{Y \in \mathbb{M}} \frac{f(Y) \, dV}{N(Y - Z)^2}
\]

is a projector onto \( \rho_1(\mathcal{H}^+) \) and, in particular, provides a reproducing formula for functions in \( \rho_1(\mathcal{H}^+) \). Similarly, if \( Z \in \mathbb{T}^- \), then the map

\[
f \mapsto P_M^-(Z) = \frac{i}{2\pi^3} \int_{Y \in \mathbb{M}} \frac{f(Y) \, dV}{N(Y - Z)^2}
\]

is a projector onto \( \rho_1(\mathcal{H}^-) \) and, in particular, provides a reproducing formula for functions in \( \rho_1(\mathcal{H}^-) \).

(The reproducing formulas for \( \rho_1(\mathcal{H}^+) \) and \( \rho_1(\mathcal{H}^-) \) were obtained in [FL1], Theorem 74.)

Next we introduce operators

\[
f \mapsto (I_{M_1}^- f)(Z_1, Z_2) = \frac{i}{2\pi^3} \lim_{z_1' \to Z_1, z_1'' \in \mathbb{T}^+} \lim_{z_2' \to Z_2, z_2'' \in \mathbb{T}^-} \int_{Y \in \mathbb{M}} \frac{f(Y) \, dV}{N(Y - Z_1') \cdot N(Y - Z_2')},
\]

where \( Z_1, Z_2 \in \mathbb{M} \) and \( N(Z_1 - Z_2) \neq 0 \). Similarly, we can switch the roles of \( Z_1 \) and \( Z_2 \) and define another operator

\[
f \mapsto (I_{M_1}^+ f)(Z_1, Z_2) = \frac{i}{2\pi^3} \lim_{z_1' \to Z_1, z_1'' \in \mathbb{T}^-} \lim_{z_2' \to Z_2, z_2'' \in \mathbb{T}^+} \int_{Y \in \mathbb{M}} \frac{f(Y) \, dV}{N(Y - Z_1') \cdot N(Y - Z_2')},
\]

where \( Z_1, Z_2 \in \mathbb{M} \) and \( N(Z_1 - Z_2) \neq 0 \). From Theorem 15 we obtain the following result:

**Theorem 22.** The \( \mathfrak{gl}(2, \mathbb{H}_C) \)-equivariant map

\[
f \mapsto ((I_{M_1}^+ + I_{M_2}^-) f)(Z_1, Z_2) \in \mathcal{H} \otimes \mathcal{H}, \quad f \in \rho_1(\mathcal{H}), \quad Z_1, Z_2 \in \mathbb{M},
\]

is well-defined, annihilates \( \rho_1(\mathcal{H}^-) \oplus \rho_1(\mathcal{H}^+) \) and satisfies

\[
M \circ ((I_{M_1}^+ + I_{M_2}^-) f) = f \quad \text{if} \quad f \in \rho_1(\mathcal{H}^0).
\]

In particular, an operator \( P^0 \) on \( \rho_1(\mathcal{H}) \)

\[
f \mapsto (P^0 f)(Z) = - \lim_{z_1, z_2 \to Z} ((I_{M_1}^+ + I_{M_2}^-) f)(Z_1, Z_2), \quad Z \in \mathbb{M},
\]

is well-defined, annihilates \( \rho_1(\mathcal{H}^-) \oplus \rho_1(\mathcal{H}^+) \) and is the identity mapping on \( \rho_1(\mathcal{H}^0) \).

Finally, the operator \( P^0 \) on \( \rho_1(\mathcal{H}) \) can be computed as follows:

\[
(P^0 f)(Z) = \frac{1}{2\pi^3} \lim_{t \to 0} \lim_{s \to 0} \left( \int_{Y \in \mathbb{M}} \frac{f(Y) \, dV}{N(Y - Z + it + s) \cdot N(Y - Z - it - s)} + \int_{Y \in \mathbb{M}} \frac{f(Y) \, dV}{N(Y - Z + it - s) \cdot N(Y - Z - it + s)} \right), \quad Z \in \mathbb{M}.
\]
9 Anti de Sitter Space

We consider a 5-dimensional space $\mathbb{R}^{1,4}$ with coordinates $(w^0, w^1, w^2, w^3, w^4)$ and metric coming from an indefinite inner product

$$\langle W, W' \rangle_{1,4} = w^0 w'^0 - w^1 w'^1 - w^2 w'^2 - w^3 w'^3 - w^4 w'^4.$$ 

Corresponding to this metric, we have a wave operator follows:

$$\square_{1,4} = \frac{\partial^2}{(\partial w^0)^2} - \frac{\partial^2}{(\partial w^1)^2} - \frac{\partial^2}{(\partial w^2)^2} - \frac{\partial^2}{(\partial w^3)^2} - \frac{\partial^2}{(\partial w^4)^2}.$$

We introduce notations

$$\mathbb{R}^{1,4}_+ = \{ (w^0, w^1, w^2, w^3, w^4) \in \mathbb{R}^{1,4}; \ w^0 > \sqrt{(w^1)^2 + (w^2)^2 + (w^3)^2 + (w^4)^2} \},$$

$$\|W\|_{1,4} = \sqrt{(w^0)^2 - (w^1)^2 - (w^2)^2 - (w^3)^2 - (w^4)^2}, \ W \in \mathbb{R}^{1,4}_+.$$

We fix a parameter $\mu > 0$ and introduce new coordinates $(\rho, v^1, v^2, v^3, v^4)$ on $\mathbb{R}^{1,4}_+$ as follows:

$$\begin{cases} 
\rho = \|W\|_{1,4}, \\
v^i = (\mu \rho)^{-1} w^i, \ i = 1, 2, 3, 4.
\end{cases}$$

Then

$$\begin{cases} 
w^0 = \mu \rho (\mu^{-2} + (v^1)^2 + (v^2)^2 + (v^3)^2 + (v^4)^2)^{1/2}, \\
w^i = \mu \rho v^i, \ i = 1, 2, 3, 4.
\end{cases}$$

For each $\rho > 0$, let us denote by $H_\rho$ the single sheet of a two-sheeted hyperboloid

$$H_\rho = \{ W \in \mathbb{R}^{1,4}; \ (w^0)^2 - (w^1)^2 - (w^2)^2 - (w^3)^2 - (w^4)^2 = \rho^2, \ w^0 > 0 \}. \quad (39)$$

Let us introduce differential operators

$$\square = \frac{\partial^2}{(\partial v^1)^2} + \frac{\partial^2}{(\partial v^2)^2} + \frac{\partial^2}{(\partial v^3)^2} + \frac{\partial^2}{(\partial v^4)^2}.$$

$$\text{deg} = v^1 \frac{\partial}{\partial v^1} + v^2 \frac{\partial}{\partial v^2} + v^3 \frac{\partial}{\partial v^3} + v^4 \frac{\partial}{\partial v^4}, \quad \widetilde{\text{deg}} f = \text{deg} f + f.$$

By direct computation we obtain:

**Lemma 23.** We have

$$\square_{1,4} = \frac{\partial^2}{\partial \rho^2} + \frac{4}{\mu} \frac{\partial}{\partial \rho} - \frac{1}{\mu^2 \rho^2} \square_\mu, \quad (40)$$

where

$$\square_\mu = \square + \mu^2 (\text{deg}^2 + 3 \text{deg}) = \square + \mu^2 \left( \widetilde{\text{deg}}^2 + \widetilde{\text{deg}} - 2 \right).$$

We think of $\frac{\partial^2}{\partial \rho^2} + \frac{4}{\mu} \frac{\partial}{\partial \rho}$ as the “radial” part of the wave operator $\square_{1,4}$ and $\square_\mu$ as the part “tangential” to the hyperboloids $H_\rho$. Note that when $\mu \to 0$, $\square_\mu$ becomes the ordinary Laplacian.

We identify the space of quaternions $\mathbb{H}$ with one sheet of a two-sheeted hyperboloid in $\mathbb{R}^{1,4}$ as follows:

$$\mathbb{H} \ni X = x^0 + ix^1 + jx^2 + kx^3 \quad \leftrightarrow \quad (\rho, v^1 = x^0, v^2 = x^1, v^3 = x^2, v^4 = x^3) \in \mathbb{R}^{1,4}_+,$$

where $\rho$ can be any fixed positive number. We study functions on $\mathbb{H}$ that are annihilated by the conformal Laplacian

$$\widetilde{\square}_\mu = \square + \mu^2 (\text{deg}^2 + 3 \text{deg} + 2) = \square + \mu^2 \left( \widetilde{\text{deg}}^2 + \widetilde{\text{deg}} \right).$$

The following lemma is verified by direct computation.

The following lemma is verified by direct computation.
Lemma 24. Let $X, Y \in \mathbb{H}$, with $Y$ fixed, and let
\[ X = \left( \sqrt{\mu^{-2} + N(X)}, x^0, x^1, x^2, x^3 \right) \quad \text{and} \quad \hat{Y} = \left( \sqrt{\mu^{-2} + N(Y)}, y^0, y^1, y^2, y^3 \right) \quad \in \mathbb{R}^{1,4}, \]
so that $\mu \rho \hat{X}, \mu \rho \hat{Y} \in H_\rho$. Then
\[
\widetilde{\deg} \left( \frac{1}{\langle \hat{X} - \hat{Y}, \hat{X} - \hat{Y} \rangle_{1,4}} \right) = \left( 1 - \frac{\sqrt{\mu^{-2} + N(Y)}}{\sqrt{\mu^{-2} + N(X)}} \right) \frac{2\mu^{-2}}{(\langle \hat{X} - \hat{Y}, \hat{X} - \hat{Y} \rangle_{1,4})^2}
\]
and
\[
\Box_{\mu} \left( \frac{1}{\langle \hat{X} - \hat{Y}, \hat{X} - \hat{Y} \rangle_{1,4}} \right) = 0.
\]

We conclude this section with the following result.

Lemma 25. Whenever $X, Y \in \mathbb{H}, X \neq Y$, we have $\langle \hat{X} - \hat{Y}, \hat{X} - \hat{Y} \rangle_{1,4} < 0$.

Proof. We use two inequalities:
\[
\sqrt{\mu^{-2} + N(X)} \sqrt{\mu^{-2} + N(Y)} \geq \mu^{-2} + \sqrt{N(X)N(Y)}
\]
and
\[
\sqrt{N(X)N(Y)} \geq x^0 y^0 + x^1 y^1 + x^2 y^2 + x^3 y^3.
\]
The first inequality is strict unless $N(X) = N(Y)$; and the second inequality is also strict unless $X$ and $Y$ are proportional with a non-negative proportionality coefficient. We have:
\[
\langle \hat{X} - \hat{Y}, \hat{X} - \hat{Y} \rangle_{1,4} = \langle \hat{X}, \hat{X} \rangle_{1,4} + \langle \hat{Y}, \hat{Y} \rangle_{1,4} - 2\langle \hat{X}, \hat{Y} \rangle_{1,4}
\]
\[
= 2\mu^{-2} - 2\sqrt{\mu^{-2} + N(X)} \sqrt{\mu^{-2} + N(Y)} + 2(x^0 y^0 + x^1 y^1 + x^2 y^2 + x^3 y^3)
\]
\[
\leq 2(x^0 y^0 + x^1 y^1 + x^2 y^2 + x^3 y^3) - 2\sqrt{N(X)N(Y)} \leq 0,
\]
and if $X \neq Y$ at least one of the inequalities is strict. \hfill \Box

10 Conformal Lie Algebra Action

Let $SO^+(1,4)$ denote the connected component of the identity element in $SO(1,4)$. In this section we describe the action of $SO^+(1,4)$ and its Lie algebra $\mathfrak{so}(1,4)$ on the space of solutions of $\Box_{\mu} \varphi = 0$. Then we extend the Lie algebra action to $\mathfrak{so}(1,5)$ (recall that the conformal Lie algebra in the classical case is $\mathfrak{sl}(2, \mathbb{H}) \simeq \mathfrak{so}(1,5)$). Complexifying, we immediately obtain an action of $\mathbb{C} \otimes \mathfrak{so}(1,5) \simeq \mathfrak{so}(6, \mathbb{C})$. The construction of the action of $\mathfrak{so}(1,5)$ will be very similar to that of the indefinite orthogonal group $O(p,q)$ acting on the solutions of the ultrahyperbolic wave equation in $\mathbb{R}^{p-1,q-1}$. See [KO] (and references therein) for a description of this action of $O(p,q)$ suitable for our purposes.

Fix a $\rho_0 > 0$ and recall that $H_{\rho_0}$ denotes the single sheet of a two-sheeted hyperboloid (39). The group $SO^+(1,4)$ acts linearly on $\mathbb{R}^{1,4}$ and preserves each $H_{\rho_0}$. Hence it acts on functions on $H_{\rho_0}$ by
\[
\pi(a) : \quad (f(W) \mapsto (\pi(a)f)(W) = f(a^{-1} \cdot W), \quad a \in SO^+(1,4).
\]

Proposition 26. This action preserves the kernel of $\Box_{\mu}$. That is, if $\varphi$ is a function on $H_{\rho_0}$ satisfying $\Box_{\mu} \varphi = 0$ and $a \in SO^+(1,4)$, then $\Box_{\mu}(\pi(a)\varphi) = 0$.  

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Proof. Let \( a \in SO^+(1, 4) \). The action of \( a \) on \( \mathbb{R}^{1,4} \) commutes with the wave operator \( \Box_{1,4} \). Hence \( \pi(a) \) commutes with the tangential part of the wave operator \( \Box_\mu \). Therefore, \( \pi(a) \) commutes with \( \Box_\mu = \Box_\mu + 2\mu^2 \).

In order to extend the action to \( \mathfrak{so}(1, 5) \) we consider a 6-dimensional space \( \mathbb{R}^{1,5} \) with coordinates \( (w^0, w^1, w^2, w^3, w^4, w^5) \) and indefinite inner product
\[
\langle W, W' \rangle_{1,5} = w^0 w^0 - w^1 w^1 - w^2 w^2 - w^3 w^3 - w^4 w^4 - w^5 w^5.
\]
The group \( SO(1, 5) \) acts linearly on \( \mathbb{R}^{1,5} \) preserving this inner product. We introduce a function \( \nu \) on \( \mathbb{R}^{1,5} \):
\[
\nu(W) = w^5, \quad W = (w^0, w^1, w^2, w^3, w^4, w^5) \in \mathbb{R}^{1,5}.
\]
We realize \( SO(1, 4) \) as the subgroup of \( SO(1, 5) \) fixing the last coordinate. We can embed \( \mathbb{R}^{1,4} \) into \( \mathbb{R}^{1,5} \) as a hyperplane \( w^5 = \text{const} \) so that \( SO(1, 4) \) preserves it; and we choose to fix a particular embedding
\[
\mathbb{R}^{1,4} \ni (w^0, w^1, w^2, w^3, w^4) \mapsto (w^0, w^1, w^2, w^3, w^4, \rho_0) \in \mathbb{R}^{1,5}.
\]
This way the hyperboloid \( H_{\rho_0} \) maps into the light cone in \( \mathbb{R}^{1,5} \)
\[
\text{Cone}_{1,5} = \{ W \in \mathbb{R}^{1,5}; (w^0)^2 - (w_1)^2 - (w^2)^2 - (w^3)^2 - (w^4)^2 - (w^5)^2 = 0 \},
\]
and this cone is obviously preserved by the \( SO(1, 5) \) action. Let \( \tilde{H}_{\rho_0} \) be the two-sheeted hyperboloid
\[
\tilde{H}_{\rho_0} = \{ W \in \text{Cone}_{1,5}; w^5 = \rho_0 \} \subset \text{Cone}_{1,5} \subset \mathbb{R}^{1,5},
\]
then \( H_{\rho_0} \) can be identified with \( \{ W \in \tilde{H}_{\rho_0}; w^0 > 0 \} \). The group \( SO(1, 5) \) acts on \( \tilde{H}_{\rho_0} \) by projective transformations:
\[
\pi(a) : W \mapsto \rho_0 \frac{a \cdot W}{\nu(a \cdot W)}, \quad a \in SO(1, 5).
\]
Of course, this action is defined only when \( \nu(a \cdot W) \neq 0 \). Then we can extend this action to functions on \( \tilde{H}_{\rho_0} \) by fixing a \( \lambda \in \mathbb{C} \) and letting
\[
\varpi_\lambda(a) : f(W) \mapsto (\varpi_\lambda(a)f)(W) = \rho_0^{-\lambda} \cdot (\nu(a^{-1} \cdot W))^\lambda \cdot f(\pi(a^{-1})W), \quad a \in SO(1, 5).
\]
Finally, we set \( \lambda = -1 \) and let \( \pi(a) = \varpi_{-1}(a) \):
\[
\pi(a) : f(W) \mapsto (\pi(a)f)(W) = \frac{\rho_0}{\nu(a^{-1} \cdot W)} \cdot f(\pi(a^{-1})W), \quad a \in SO(1, 5).
\]
This action extends previously defined action \( (41) \) of \( SO^+(1, 4) \). Differentiating, we obtain an action of the Lie algebra \( \mathfrak{so}(1, 5) \) on functions on \( \tilde{H}_{\rho_0} \) and \( H_{\rho_0} \), which we still denote by \( \pi \). Complexifying, we immediately obtain an action of \( \mathbb{C} \otimes \mathfrak{so}(1, 5) \simeq \mathfrak{so}(6, \mathbb{C}) \).

**Theorem 27.** The \( \pi \)-action of the Lie algebra \( \mathfrak{so}(6, \mathbb{C}) \) preserves the kernel of \( \Box_\mu \). That is, if \( \varphi \) is a function on \( H_{\rho_0} \) satisfying \( \Box_\mu \varphi = 0 \) and \( h \in \mathfrak{so}(6, \mathbb{C}) \), then \( \Box_\mu (\pi(h)\varphi) = 0 \).

**Proof.** It is sufficient to prove the result for \( h \in \mathfrak{so}(1, 5) \subset \mathfrak{so}(6, \mathbb{C}) \) only. For \( h \in \mathfrak{so}(1, 4) \subset \mathfrak{so}(1, 5) \) the result is true by Proposition 26. As a Lie algebra, \( \mathfrak{so}(1, 5) \) is generated by \( \mathfrak{so}(1, 4) \) and the Lie algebra of the one-parameter family of hyperbolic rotations in the \( (w^0, w^5) \)-plane:
\[
a_t : w^0 \mapsto w^0 \cosh t + w^5 \sinh t, \quad w^5 \mapsto w^5 \cosh t + w^0 \sinh t, \quad t \in \mathbb{R},
\]
\( w^1, w^2, w^3 \) and \( w^4 \) stay unchanged. To compute \( \frac{d}{dt}|_{t=0}\pi(a_t) \), we let \( t \to 0 \) and working modulo terms of order \( t^2 \) we get

\[
(\pi(a_t)\varphi)(W) = \frac{\rho_0}{\rho_0 - tw^0} \cdot \varphi\left( \frac{\rho_0 - tw^0}{\rho_0 - tw^0}, \frac{\rho_0}{\rho_0 - tw^0}, \frac{\rho_0}{\rho_0 - tw^0}, \frac{\rho_0}{\rho_0 - tw^0} \right).
\]

Rewriting it in \((\rho, v^1, v^2, v^3, v^4)\) coordinates, we obtain

\[
(\pi(a_t)\varphi)(W) = \frac{\rho_0}{\rho_0 - tw^0} \cdot \varphi\left( \frac{\rho_0}{\rho_0 - tw^0}, \frac{\rho_0}{\rho_0 - tw^0}, \frac{\rho_0}{\rho_0 - tw^0}, \frac{\rho_0}{\rho_0 - tw^0} \right).
\]

Hence

\[
\frac{d}{dt}(\pi(a_t)\varphi)|_{t=0} = \frac{w^0}{\rho_0} \varphi + \frac{w^0}{\rho_0} \deg \varphi = \frac{w^0}{\rho_0} \deg \varphi = (1 + \mu^2N(X))^{1/2} \deg \varphi,
\]

since \( w^0 = \rho_0(1 + \mu^2N(X))^{1/2} \), where \( N(X) = (v^1)^2 + (v^2)^2 + (v^3)^2 + (v^4)^2 \). Finally, the theorem follows from the lemma below. \( \square \)

**Lemma 28.** The operator \( \varphi \mapsto (1 + \mu^2N(X))^{1/2} \deg \varphi \) preserves the kernel of \( \bar{\Box}_\mu \).

**Proof.** We need to show that if \( \varphi \) is a function on \( H_{\rho_0} \) satisfying \( \bar{\Box}_\mu \varphi = 0 \), then \( \bar{\Box}_\mu ((\mu^{-2} + N(X))^{1/2} \deg \varphi) = 0 \). For this purpose we compute the following commutators of operators:

\[
\left[ \Box, (\mu^{-2} + N(X))^{1/2} \right] = \Box (\mu^{-2} + N(X))^{1/2} + 2 \sum_{i=1}^{4} \left( \frac{\partial}{\partial v^i} (\mu^{-2} + N(X))^{1/2} \right) \cdot \frac{\partial}{\partial v^i} - \frac{1}{(\mu^{-2} + N(X))^{1/2}} - \frac{2}{(\mu^{-2} + N(X))^{3/2}} + \frac{2N(X)}{(\mu^{-2} + N(X))^{1/2}} \deg,
\]

\[
\left[ \deg, (\mu^{-2} + N(X))^{1/2} \right] = \deg (\mu^{-2} + N(X))^{1/2} = N(X) \cdot (\mu^{-2} + N(X))^{-1/2},
\]

\[
\left[ \deg^2, (\mu^{-2} + N(X))^{1/2} \right] = \deg \circ \left[ \deg, (\mu^{-2} + N(X))^{1/2} \right] + \left[ \deg, (\mu^{-2} + N(X))^{1/2} \right] \circ \deg
\]

\[
= \frac{2N(X)}{(\mu^{-2} + N(X))^{1/2}} - \frac{N(X)^2}{(\mu^{-2} + N(X))^{3/2}} + \frac{2N(X)}{(\mu^{-2} + N(X))^{1/2}} \deg,
\]

\[
\left[ \bar{\Box}_\mu, (\mu^{-2} + N(X))^{1/2} \right] =
\]

\[
(\mu^{-2} + N(X))^{-1/2} \left( 4 - \frac{N(X)}{(\mu^{-2} + N(X))} + 2 \deg + \mu^2 \left( 5N(X) - \frac{N(X)^2}{(\mu^{-2} + N(X))} + 2N(X) \deg \right) \right)
\]

\[
= 2\mu^2 (\mu^{-2} + N(X))^{1/2} (\deg + 2).
\]

Finally, we get:

\[
\bar{\Box}_\mu ((\mu^{-2} + N(X))^{1/2} \deg \varphi) = (\mu^{-2} + N(X))^{1/2} \bar{\Box}_\mu \deg \varphi + \left[ \bar{\Box}_\mu, (\mu^{-2} + N(X))^{1/2} \right] \deg \varphi
\]

\[
= (\mu^{-2} + N(X))^{1/2} \left( 2\Box + 2\mu^2 (\deg + 2) \deg \right) \varphi = 2(\mu^{-2} + N(X))^{1/2} \bar{\Box}_\mu \varphi = 0.
\]

\( \square \)
11 Extension of Harmonic Functions to $\mathbb{R}^{1,4}$

If we identify the group $SU(2)$ with the unit sphere in $\mathbb{H}$, then functions on $SU(2)$ can be extended to $\mathbb{H}^\times = \mathbb{H} \setminus \{0\}$ as harmonic functions. If we require such an extension to be regular either at the origin or at infinity, then it is unique. For example, let us consider the matrix coefficients of $SU$ extended to $\mathbb{H}^\times$ as $t_{m,n}^l(\mathbb{X})$ which are homogeneous polynomials of degree $2l$ – hence regular at the origin – or as $N(\mathbb{X})^{-2l-1} \cdot t_{m,n}^l(\mathbb{X})$ which are homogeneous rational functions of degree $-(2l + 2)$ – hence regular at infinity – and in both cases

$$\square t_{m,n}^l(\mathbb{X}) = 0, \quad \square (t_{m,n}^l(\mathbb{X}) \cdot N(\mathbb{X})^{-2l-1}) = 0.$$ 

In this section we start with a function on the unit sphere $S^3$ centered at the origin in $\mathbb{R}^4$, realize $\mathbb{R}^4$ as a hyperplane $\{w^0 = \text{const}\}$ inside $\mathbb{R}^{1,4}$ and find the function’s extensions to $\mathbb{R}_{+}^{1,4}$ which are annihilated both by the wave operator $\square_{1,4}$ and the conformal Laplacian $\square_\mu$. Let $(r, \overrightarrow{\mathbb{n}})$ be the spherical coordinates of $\mathbb{R}^4$ spanned by $w^1, w^2, w^3, w^4$, so that

$$r = \sqrt{(w^1)^2 + (w^2)^2 + (w^3)^2 + (w^4)^2} \quad \text{and} \quad \overrightarrow{\mathbb{n}} \in S^3.$$ 

Then

$$\frac{\partial^2}{(\partial w^1)^2} + \frac{\partial^2}{(\partial w^2)^2} + \frac{\partial^2}{(\partial w^3)^2} + \frac{\partial^2}{(\partial w^4)^2} = \frac{\partial^2}{\partial r^2} + \frac{3}{r} \frac{\partial}{\partial r} + \frac{\Delta_{S^3}}{r^2},$$

where $\Delta_{S^3}$ denotes the spherical Laplacian on the unit sphere in $\mathbb{R}^4$. In particular, we obtain a set of coordinates on $\mathbb{R}_{+}^{1,4}$:

$$(w^0, w^1, w^2, w^3, w^4) \quad \leftrightarrow \quad (w^0, r, \overrightarrow{\mathbb{n}}).$$

We perform another change of coordinates

$$(w^0, r, \overrightarrow{\mathbb{n}}) \quad \leftrightarrow \quad (\rho, \theta, \overrightarrow{\mathbb{n}})$$

with

$$w^0 = \rho \cosh \theta, \quad r = \rho \sinh \theta, \quad \rho = \sqrt{(w^0)^2 - r^2}, \quad \tanh \theta = r/w^0.$$ 

Then

$$\frac{\partial}{\partial w^0} = \cosh \theta \frac{\partial}{\partial \rho} - \frac{\sinh \theta}{\rho} \frac{\partial}{\partial \theta}, \quad \frac{\partial}{\partial r} = -\sinh \theta \frac{\partial}{\partial \rho} + \frac{\cosh \theta}{\rho} \frac{\partial}{\partial \theta},$$

and it follows that

$$\square_{1,4} = \frac{\partial^2}{(\partial w^0)^2} - \frac{\partial^2}{\partial r^2} - \frac{3}{r} \frac{\partial}{\partial r} - \frac{\Delta_{S^3}}{r^2} = \frac{\partial^2}{\partial \rho^2} + \frac{4}{\rho} \frac{\partial}{\partial \rho} - \frac{1}{\rho^2} \frac{\partial^2}{\partial \theta^2} - \frac{3}{\rho^2} \sinh \theta \frac{\partial}{\partial \theta} - \frac{\Delta_{S^3}}{\rho^2 \sinh^2 \theta}.$$ 

Now we look for solutions of $\square_{1,4} \varphi(W) = 0$ in the separated form

$$\varphi(W) = \rho^\lambda \cdot s_l(\theta) \cdot t_{m,n}^l(\overrightarrow{\mathbb{n}}),$$

where $t_{m,n}^l$’s are the matrix coefficients of $SU(2)$ defined by (14). Since $r^{2l} \cdot t_{m,n}^l(\overrightarrow{\mathbb{n}})$ are harmonic homogeneous polynomials in $w^1, \ldots, w^4$ of degree $2l$, it follows that the matrix coefficients $t_{m,n}^l$’s are eigenfunctions for $\Delta_{S^3}$:

$$\Delta_{S^3} t_{m,n}^l(\overrightarrow{\mathbb{n}}) = -4l(l+1) t_{m,n}^l(\overrightarrow{\mathbb{n}}).$$
Moreover, any eigenfunction of $\Delta_{S^3}$ is a linear combination of $t_{m \underline{n}}^l$’s.

Since $\square_\mu$ does not depend on $\rho$, by (40),

$$\square_{1.4}(\rho^\lambda \cdot s_l(\theta) \cdot t_{m \underline{n}}^l) = 0 \iff (\square_\mu - \lambda(\lambda + 3)\mu^2)(s_l(\theta) \cdot t_{m \underline{n}}^l) = 0.$$

Recall that we are looking for functions annihilated by $\square_\mu = \square_\mu + 2\mu^2$ as well. Hence

$$\lambda(\lambda + 3) + 2 = 0 \quad \text{and} \quad \lambda = -1 \quad \text{or} \quad \lambda = -2. \quad (42)$$

The equation $\square_{1.4}\varphi(W) = 0$ becomes an ordinary differential equation for $s_l(\theta)$:

$$0 = \square_{1.4}\varphi(W) = \left( \frac{\partial^2}{\partial \rho^2} + \frac{4}{\rho} \frac{\partial}{\partial \rho} - \frac{1}{\rho^2} \frac{\partial^2}{\partial \theta^2} - 3 \frac{\cosh \theta}{\rho^2 \sinh \theta} \frac{\partial}{\partial \theta} - \frac{\Delta_{S^3}}{\rho^2 \sinh^2 \theta} \right) \rho^\lambda \cdot s_l(\theta) \cdot t_{m \underline{n}}^l = \rho^{\lambda-2} \cdot t_{m \underline{n}}^l \cdot \left( \lambda(\lambda - 1) + 4\lambda - \frac{\partial^2}{\partial \theta^2} - 3 \frac{\cosh \theta}{\sinh \theta} \frac{\partial}{\partial \theta} + \frac{4l(l + 1)}{\sinh^2 \theta} \right) s_l(\theta).$$

Thus, the function $s_l(\theta)$ satisfies a differential equation

$$\left( \frac{d^2}{d\theta^2} + 3 \frac{\cosh \theta}{\sinh \theta} \frac{d}{d\theta} - \frac{4l(l + 1)}{\sinh^2 \theta} - \lambda(\lambda + 3) \right) s_l(\theta) = 0.$$

Changing the variable $\theta$ to $t = \cosh \theta$ and using $\frac{d}{dt} = \sinh \theta \frac{d}{d\theta}$, we can rewrite this equation as

$$\left( (t^2 - 1) \frac{d^2}{dt^2} + 4t \frac{d}{dt} - \frac{4l(l + 1)}{t^2 - 1} - \lambda(\lambda + 3) \right) s_l(t) = 0.$$

But $\lambda(\lambda + 3) = -2$ by (42), so

$$\left( (t^2 - 1) \frac{d^2}{dt^2} + 4t \frac{d}{dt} - \frac{4l(l + 1)}{t^2 - 1} + 2 \right) s_l(t) = 0.$$

It is easy to verify directly that

$$\frac{(t - 1)^l}{(t + 1)^{l+1}} \quad \text{and} \quad \frac{(t + 1)^l}{(t - 1)^{l+1}}, \quad l = 0, 1, 2, \ldots, 1/2, 1, 3/2, 2, \ldots,$$

are two linearly independent solutions of this equation. Thus we obtain four families of functions on $\mathbb{R}^1$ that simultaneously satisfy $\square_{1.4}\varphi = 0$ and $\square_\mu \varphi = 0$:

$$\rho^\lambda \cdot \frac{(\cosh \theta - 1)^l}{(\cosh \theta + 1)^{l+1}} \cdot t_{m \underline{n}}^l \quad \text{and} \quad \rho^\lambda \cdot \frac{(\cosh \theta + 1)^l}{(\cosh \theta - 1)^{l+1}} \cdot t_{m \underline{n}}^l,$$

$$\lambda = -1 \quad \text{or} \quad \lambda = -2, \quad l = 0, 1/2, 1, 3/2, 2, \ldots.$$

Since $\mu^2 \rho^2 N(X) = r^2 = \rho^2 \sinh^2 \theta$, we have $\sinh^2 \theta = \mu^2 N(X)$ and $\cosh^2 \theta = 1 + \mu^2 N(X)$. Then we can rewrite our functions using

$$t_{m \underline{n}}^l = t_{m \underline{n}}^l(X) \cdot N(X)^{-l} = \mu^{2l} \cdot (\sinh \theta)^{-2l} \cdot t_{m \underline{n}}^l(X) = \mu^{2l} \cdot (\cosh \theta - 1)^{-l} \cdot (\cosh \theta + 1)^{-l} \cdot t_{m \underline{n}}^l(X).$$

We summarize the results of this section as a proposition.
Proposition 29. We have four families of functions on $\mathbb{R}^{1,4}_+$ that simultaneously satisfy $\Box_{1,4}\phi = 0$ and $\Box_\mu \phi = 0$

\[
\rho^\lambda \cdot t_{m,n}^l(X) \begin{cases} \frac{(1 + \mu^2 N(X))^{1/2} + 1}{2l+1} & \text{if} \quad \lambda = 1, \\
(1 + \mu^2 N(X))^{1/2} - 1 & \text{if} \quad \lambda = 0, \end{cases}
\]

where $\rho \equiv \sqrt{(w^0)^2 - (w^1)^2 - (w^2)^2 - (w^3)^2 - (w^4)^2}$ and $X = (x^0, x^1, x^2, x^3) = (w^1/w, w^2/w, w^3/w, w^4/w)$.

Up to proportionality coefficients, these functions extend the matrix coefficient functions $t_{m,n}^l(\overline{\partial})$ on $S^3 = \{ W \in H_\rho; (w^1)^2 + (w^2)^2 + (w^3)^2 + (w^4)^2 = 1 \} \subset \mathbb{R}^{1,4}_+$.

Moreover, any other extension of $t_{m,n}^l(\overline{\partial})$ to $\mathbb{R}^{1,4}_+$ satisfying both $\Box_{1,4}\phi = 0$ and $\Box_\mu \phi = 0$ is a linear combination of functions (43).

12 Spaces of Solutions of $\overline{\partial}_\mu \phi = 0$ and an Invariant Bilinear Pairing

We denote by $H_{\mu}^+$ the space of solutions of $\Box_\mu \phi = 0$ on $\mathbb{R}^\times$; these solutions are real analytic functions. We introduce algebraic subspaces

\[
H_{\mu}^+ = \mathbb{C}\text{-span of} \frac{t_{m,n}^l(X)}{((1 + \mu^2 N(X))^{1/2} + 1)^{2l+1}}, \quad l = 0, 1, 2, \ldots, \quad m, n = -l, -l+1, \ldots, l,
\]

\[
H_{\mu}^- = \mathbb{C}\text{-span of} \frac{t_{m,n}^l(X)}{((1 + \mu^2 N(X))^{1/2} - 1)^{2l+1}}, \quad l = 0, 1, 2, \ldots, \quad m, n = -l, -l+1, \ldots, l,
\]

and $H_{\mu} = H_{\mu}^+ \oplus H_{\mu}^-$. Note that when $\mu \to 0$,

\[
\frac{2^{2l+1} t_{m,n}^l(X)}{((1 + \mu^2 N(X))^{1/2} + 1)^{2l+1}} \to t_{m,n}^l(X)
\]

and

\[
\frac{2^{-2l-1} t_{m,n}^l(X)}{((1 + \mu^2 N(X))^{1/2} - 1)^{2l+1}} \to t_{m,n}^l(X) \cdot N(X)^{-2l-1}.
\]

Since the restrictions of $t_{m,n}^l(X) \cdot ((1 + \mu^2 N(X))^{1/2} \pm 1)^{-2l-1}$ to the unit ball in $\mathbb{H}$ are dense in the space of all analytic functions on that ball, $\mathcal{H}_{\mu}$ is dense in $\mathcal{H}_{\mu}$, justifying the notation. Taking closures we obtain a decomposition $\overline{\mathcal{H}}_{\mu} = \overline{\mathcal{H}}_{\mu}^+ \oplus \overline{\mathcal{H}}_{\mu}^-$. The space $\mathcal{H}_{\mu}$ can be characterized as the space of all $SO(4)$-finite solutions of $\Box_\mu \phi = 0$ on $\mathbb{H}^\times$. Then $\overline{\mathcal{H}}_{\mu}^+$ can be characterized as the subspace of $\mathcal{H}_{\mu}$ consisting of functions that are regular at the origin. Finally, $\overline{\mathcal{H}}_{\mu}^-$ can be characterized as the subspace of $\mathcal{H}_{\mu}$ consisting of functions that decay at infinity (or “regular at infinity”).

We introduce a bilinear pairing between $\overline{\mathcal{H}}_{\mu}^+$ and $\overline{\mathcal{H}}_{\mu}^-$:

\[
(\varphi_1, \varphi_2)_\mu = \frac{\sqrt{1 + \mu^2 R^2}}{2\pi^2} \int_{X \in \mathcal{S}_R^3} \overline{\varphi_1}(X) \cdot \varphi_2(X) \frac{dS}{R}
\]

\[
= -\frac{\sqrt{1 + \mu^2 R^2}}{2\pi^2} \int_{X \in \mathcal{S}_R^3} \varphi_1(X) \cdot \overline{\varphi_2}(X) \frac{dS}{R}, \quad \varphi_1 \in \overline{\mathcal{H}}_{\mu}^+, \varphi_2 \in \overline{\mathcal{H}}_{\mu}^-, \quad (44)
\]
where $S^3_R$ denotes a sphere of radius $R > 0$ in $\mathbb{H}$ centered at the origin and $dS$ denotes the standard Euclidean measure on $S^3_R$ inherited from $\mathbb{H}$.

**Proposition 30.** The two expressions in (44) agree; the resulting bilinear pairing is $SO^+(1, 4)$-invariant, $\mathfrak{so}(6, \mathbb{C})$-invariant, non-degenerate and independent of $R$. Moreover,

\[
\left( \frac{t_{m,n}^l \left( X \right)}{\left( (1 + \mu^2 N(X))^{1/2} + 1 \right)^{2l+1}}, \frac{t_{m',n'}^{l'} \left( X^+ \right)}{\left( (1 + \mu^2 N(X))^{1/2} - 1 \right)^{2l'+1}} \right)_{\mu} = \delta_{ll'} \delta_{mm'} \frac{\delta_{n'n'}}{\mu^{4l+2}}. \tag{45}
\]

**Proof.** Using 

\[
\text{deg} \left( 1 + \mu^2 N(X) \right)^{1/2} = \mu^2 N(X) \cdot (1 + \mu^2 N(X))^{-1/2}, \tag{46}
\]

we obtain 

\[
\tilde{\text{deg}} \left( \frac{t_{m,n}^l \left( X \right)}{\left( (1 + \mu^2 N(X))^{1/2} + 1 \right)^{2l+1}} \right) = \frac{\pm (2l + 1) t_{m,n}^l \left( X \right)}{\left( (1 + \mu^2 N(X))^{1/2} \right) \cdot \left( (1 + \mu^2 N(X))^{1/2} + 1 \right)^{2l+1}}.
\]

Then (45) follows from the orthogonality relations (17).

Since these basis functions are dense in $\mathcal{H}_\mu^+$ and $\mathcal{H}_\mu^-$ respectively, this computation proves that the two expressions in (44) agree, independent of $R > 0$ and the resulting bilinear pairing is non-degenerate. It remains to prove that it is $SO^+(1, 4)$-invariant and $\mathfrak{so}(6, \mathbb{C})$-invariant. The proof will be given in Corollary 33. \qed

### 13 Poisson Formula

In this section we prove a Poisson-type formula for functions on $\mathbb{H}$ annihilated by $\hat{\mathcal{H}}_\mu$. As an intermediate step, we derive an expansion for $(\hat{X} - \hat{Y}, \hat{X} - \hat{Y})^{-1}$ similar to the matrix coefficient expansions for $N(X - Y)^{-1}$ given by Proposition 25 from [FL1] and restated here as equation (35). We recall the notations of Lemma 24: for $X, Y \in \mathbb{H}$, let

\[
\hat{X} = (\sqrt{\mu^2 + N(X)}, x^0, x^1, x^2, x^3) \quad \text{and} \quad \hat{Y} = (\sqrt{\mu^2 + N(Y)}, y^0, y^1, y^2, y^3) \in \mathbb{H}_4^+.
\]

**Proposition 31.** We have the following expansion:

\[
-\frac{1}{\langle \hat{X} - \hat{Y}, \hat{X} - \hat{Y} \rangle_{1,4}} = \sum_{l,m,n} \frac{t_{m,n}^l \left( X \right)}{\left( (1 + \mu^2 N(X))^{1/2} + 1 \right)^{2l+1}} \cdot \frac{\mu^{4l+2} \cdot t_{m,n}^l \left( Y^+ \right)}{\left( (1 + \mu^2 N(Y))^{1/2} - 1 \right)^{2l+1}},
\]

which converges pointwise absolutely in the region \{(X, Y) \in \mathbb{H} \times \mathbb{H}; N(X) < N(Y)\}. The sum is taken first over all $m, n = -l, -l+1, \ldots, l$, then over $l = 0, \frac{1}{2}, 1, \frac{3}{2}, 2, \ldots$.

**Proof.** Let $X, Y \in \mathbb{H}$ and

\[
\bar{\bar{u}} = \frac{X}{\sqrt{N(X)}}, \quad \bar{\bar{v}} = \frac{Y}{\sqrt{N(Y)}} \in SU(2) \subset \mathbb{H},
\]

then $\bar{\bar{u}}^{-1} \bar{\bar{v}}$ is similar to a diagonal matrix $\begin{pmatrix} \lambda & 0 \\ 0 & \lambda^{-1} \end{pmatrix}$, where $\lambda \in \mathbb{C}$, $|\lambda| = 1$. Define $\theta_1, \theta_2, t_1$ and $t_2$ by

\[
\sinh \theta_1 = \mu \sqrt{N(X)}, \quad \sinh \theta_2 = \mu \sqrt{N(Y)}, \quad t_1 = \cosh \theta_1, \quad t_2 = \cosh \theta_2. \tag{47}
\]
Using the multiplicativity property of matrix coefficients (15), we compute:

\[
\sum_{l,m,n} \frac{t_{m,n}^l(X)}{((1 + \mu^2 N(X))^{1/2} + 1)^{2l+1}} \cdot \frac{\mu^{4l+2} \cdot t_{m,n}^l(Y)}{((1 + \mu^2 N(Y))^{1/2} - 1)^{2l+1}} = \mu^2 \sum_{l} \frac{(t_1 - 1)^l}{(t_1 + 1)^{l+1}} \cdot \frac{(t_2 + 1)^l}{(t_2 - 1)^{l+1}} \cdot \chi(l) \cdot \theta \cdot \theta^{-1}
\]

\[
= \frac{\mu^2}{\lambda - \lambda^{-1}} \sum_l \frac{(t_1 - 1)^l}{(t_1 + 1)^{l+1}} \cdot \frac{(t_2 + 1)^l}{(t_2 - 1)^{l+1}} \cdot (\lambda^{2l+1} - \lambda^{-2l-1}).
\]

Let

\[
a = (e^{\theta_1/2} + e^{-\theta_1/2})(e^{\theta_2/2} - e^{-\theta_2/2}), \quad b = (e^{\theta_1/2} - e^{-\theta_1/2})(e^{\theta_2/2} + e^{-\theta_2/2}),
\]

then

\[
\sum_{l,m,n} \frac{t_{m,n}^l(X)}{((1 + \mu^2 N(X))^{1/2} + 1)^{2l+1}} \cdot \frac{\mu^{4l+2} \cdot t_{m,n}^l(Y)}{((1 + \mu^2 N(Y))^{1/2} - 1)^{2l+1}} = \frac{4\mu^2(\lambda - \lambda^{-1})^{-1}}{(e^{\theta_1} + e^{-\theta_1} + 2)(e^{\theta_2} + e^{-\theta_2} - 2)} \sum_l a^{-2l} \cdot b^{2l} \cdot (\lambda^{2l+1} - \lambda^{-2l-1})
\]

\[
= \frac{4\mu^2}{(\lambda - \lambda^{-1})a} \left( \frac{\lambda}{a - \lambda b} - \frac{\lambda^{-1}}{a - \lambda^{-1}b} \right) = \frac{4\mu^2}{(a - \lambda b)(a - \lambda^{-1}b)} = \frac{4\mu^2}{N(b \, \overrightarrow{u} - a \, \overrightarrow{v})}.
\]

Since \(X = \mu^{-1} \sinh \theta_1 \overrightarrow{u}\) and \(Y = \mu^{-1} \sinh \theta_2 \overrightarrow{v}\),

\[
\frac{4\mu^2}{N(b \, \overrightarrow{u} - a \, \overrightarrow{v})} = 4\mu^2 \left[ N \left( \frac{\mu bX}{\sinh \theta_1} - \frac{\mu aY}{\sinh \theta_2} \right) \right]^{-1}
\]

\[
= \left[ N \left( \frac{e^{\theta_2/2} + e^{-\theta_2/2}}{e^{\theta_1/2} + e^{-\theta_1/2}} X - \frac{e^{\theta_1/2} + e^{-\theta_1/2}}{e^{\theta_2/2} + e^{-\theta_2/2}} Y \right) \right]^{-1} = \frac{(\cosh \theta_1 + 1)(\cosh \theta_2 + 1)}{N((\cosh \theta_2 + 1)X - (\cosh \theta_1 + 1)Y)}
\]

\[
= \mu^{-2} \cosh \theta_1 \cosh \theta_2 - \mu^{-2} - (x^0 y^0 + x^1 y^1 + x^2 y^2 + x^3 y^3)
\]

\[
= \frac{1}{(X, X)_{1,4} + (Y, Y)_{1,4} - 2(X, Y)_{1,4}} = \frac{1}{(X - Y, X - Y)_{1,4}}.
\]

This expansion holds whenever \(|b/a| < 1\). Since

\[
\frac{b}{a} = \tanh(\theta_1/2) \geq 0
\]

and \(\tanh \theta\) is monotone increasing, the expansion holds whenever \(\theta_1 < \theta_2\) or, equivalently, \(N(X) < N(Y)\).

We introduce a notation

\[
K_\mu(X, Y) = \frac{1}{(X - Y, X - Y)_{1,4}}.
\]

Now we are ready to prove the Poisson-type formula. Let \(S^3\) denote a sphere of radius \(R\) in \(\mathbb{H}\) centered at the origin.
Theorem 32. Let \( \varphi \) be a real analytic solution of \( \Box_\mu \varphi = 0 \) defined on a closed ball \( \{ X \in \mathbb{H}; N(X) \leq R^2 \} \), for some \( R > 0 \). Then, for all \( Y \in \mathbb{H} \) with \( N(Y) < R^2 \),

\[
\varphi(Y) = (\varphi(X), K_\mu(X, Y))_\mu
\]

\[
= \frac{1 + \mu^2R^2}{2\pi^2} \int_{X \in S^3_R} (\text{deg}_X)(X) \cdot K_\mu(X, Y) \frac{dS}{R}
\]

\[
= -\frac{1 + \mu^2R^2}{2\pi^2} \int_{X \in S^3_R} (\text{deg}_X K_\mu)(X, Y) \cdot \varphi(X) \frac{dS}{R}.
\]

Similarly, suppose \( \varphi \) is a real analytic solution of \( \Box_\mu \varphi = 0 \) defined on a closed set \( \{ X \in \mathbb{H}; N(X) \geq R^2 \} \), for some \( R > 0 \), and regular at infinity. Then, for all \( Y \in \mathbb{H} \) with \( N(Y) > R^2 \),

\[
\varphi(Y) = (K_\mu(X, Y), \varphi(X))_\mu
\]

\[
= -\frac{1 + \mu^2R^2}{2\pi^2} \int_{X \in S^3_R} (\text{deg}_X)(X) \cdot K_\mu(X, Y) \frac{dS}{R}
\]

\[
= \frac{1 + \mu^2R^2}{2\pi^2} \int_{X \in S^3_R} (\text{deg}_X K_\mu)(X, Y) \cdot \varphi(X) \frac{dS}{R}.
\]

Proof. It is sufficient to prove the formulas when

\[
\varphi(X) = \frac{t^i_{m\mathbb{R}}(X)}{(1 + \mu^2N(X))^{1/2} \pm 1}^{2|l|+1}.
\]

Then the result follows from the expansion of the kernel \( K_\mu(X, Y) \) and orthogonality relations (45).

\[\square\]

Corollary 33. The bilinear pairing (44) is \( SO^+(1,4) \)-invariant and \( \text{so}(6,\mathbb{C}) \)-invariant.

Proof. Since the group is connected, to prove \( SO^+(1,4) \)-invariance, it is sufficient to show invariance for \( a \in SO^+(1,4) \) sufficiently close to the identity only. Choose \( R_1, R_2 \) such that \( 0 < R_2 < R < R_1 \) and, using the Poisson formula, write

\[
\varphi_i(X) = (-1)^{i+1} \sqrt{1 + \mu^2R^2_i} \int_{Y_i \in S^3_{R_i}} (\text{deg}_Y)(Y_i) \cdot K_\mu(X, Y_i) \frac{dS}{R_i}, \quad i = 1, 2.
\]

In short,

\[
\varphi_1(X) = (\varphi_1(Y_1), K_\mu(X, Y_1))_\mu \quad \text{and} \quad \varphi_2(X) = (K_\mu(X, Y_2), \varphi_2(Y_2))_\mu.
\]

Then

\[
((\pi(a)\varphi_1)(X), (\pi(a)\varphi_2)(X))_\mu
\]

\[
= \left( (\varphi_1(Y_1), \pi(a)X K_\mu(X, Y_1))_\mu, (\pi(a)X K_\mu(X, Y_2), \varphi_2(Y_2))_\mu \right)_\mu
\]

\[
= \left( (\varphi_1(Y_1), K_\mu(X, Y_1))_\mu, (K_\mu(X, Y_2), \varphi_2(Y_2))_\mu \right)_\mu = (\varphi_1(X), \varphi_2(X))_\mu
\]

because the Poisson formula is \( SO^+(1,4) \)-equivariant and

\[
(\pi(a)X K_\mu(X, Y_1), \pi(a)X K_\mu(X, Y_2))_\mu
\]

\[
= (\pi(a)Y_1 \circ \pi(a)X K_\mu(X, Y_1), K_\mu(X, Y_2))_\mu = (K_\mu(X, Y_1), K_\mu(X, Y_2))_\mu.
\]
Since the action of $\mathfrak{so}(6, \mathbb{C})$ is generated by the actions of $\mathfrak{so}(1, 4)$ and the operator $\varphi \mapsto (1 + \mu^2 N(X))^{1/2} \deg \varphi$, to prove $\mathfrak{so}(6, \mathbb{C})$-invariance, it is sufficient to prove invariance under the operator $\varphi \mapsto (1 + \mu^2 N(X))^{1/2} \deg \varphi$ only. By Lemma 24,

\[
(1 + \mu^2 N(X))^{1/2} \deg_x K_\mu (X, Y) = \frac{2}{\mu^2} \left( 1 + \mu^2 N(Y) \right)^{1/2} - \left( (X - Y, X - Y)_{1,4} \right)^2
\]

and then the proof continues in exactly the same way as for $SO^+(1, 4)$-invariance. \qed

14 Regular Functions

In order to define analogues of left and right regular functions, we need to factor $\tilde{\Box}_\mu$ as a product of two Dirac-like operators. The factorization

\[
\Box = \nabla\nabla^+ = \nabla^+\nabla \quad \text{can be rewritten as} \quad \begin{pmatrix} 0 & \nabla^+ \\ \nabla & 0 \end{pmatrix}^2 = \begin{pmatrix} \Box & 0 \\ 0 & \Box \end{pmatrix} = \Box \cdot I_{2 \times 2},
\]

and

\[
\begin{pmatrix} 0 & \nabla^+ \\ \nabla & 0 \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} = 0 \quad \iff \quad \nabla f_1 = 0 \quad \text{and} \quad \nabla^+ f_2 = 0,
\]

i.e. $f_2$ is left-regular and $f_1$ is anti-left-regular.

**Proposition 34.** Let

\[
\nabla_\mu = \begin{pmatrix} \mu (X \nabla - \tilde{\deg}) & (1 + \mu^2 N(X))^{1/2} \nabla^+ \\ (1 + \mu^2 N(X))^{1/2} \nabla & \mu (X^+ \nabla^+ - \tilde{\deg}) \end{pmatrix},
\]

then we have a factorization

\[
\tilde{\Box}_\mu = \nabla_\mu (\nabla_\mu - \mu).
\]

**Proof.** We use the following identities:

\[
\nabla (1 + \mu^2 N(X))^{1/2} = \frac{\mu^2 X^+}{(1 + \mu^2 N(X))^{1/2}}, \quad \nabla^+ (1 + \mu^2 N(X))^{1/2} = \frac{\mu^2 X}{(1 + \mu^2 N(X))^{1/2}}, \quad (50)
\]

\[
X^+ \nabla^+ + \nabla X = \nabla^+ X^+ + X \nabla = 2(2 + \deg), \quad (51)
\]

the last identity in turn implies

\[
(X \nabla - \tilde{\deg})^2 = (X^+ \nabla^+ - \tilde{\deg})^2 = \tilde{\deg}^2 - N(X) \Box. \quad (52)
\]

First, we find that $\nabla^2_\mu$ is equal to

\[
\begin{pmatrix}
\mu^2 (X \nabla - \tilde{\deg})^2 + \\
(1 + \mu^2 N(X))^{1/2} \nabla^+ (1 + \mu^2 N(X))^{1/2} \nabla \\
\mu (X^+ \nabla^+ - \tilde{\deg}) (1 + \mu^2 N(X))^{1/2} \nabla \\
\mu (1 + \mu^2 N(X))^{1/2} \nabla (X \nabla - \tilde{\deg})
\end{pmatrix} + \mu (1 + \mu^2 N(X))^{1/2} \nabla^+ (X^+ \nabla^+ - \tilde{\deg})
\]

and

\[
\begin{pmatrix}
\mu (X \nabla - \tilde{\deg}) (1 + \mu^2 N(X))^{1/2} \nabla^+ \\
\mu^2 X^+ (1 + \mu^2 N(X))^{1/2} \nabla \\
\mu^2 X + \nabla (1 + \mu^2 N(X))^{1/2} \nabla^+ (X^+ \nabla^+ - \tilde{\deg})
\end{pmatrix} + \mu^2 (X^+ \nabla^+ - \tilde{\deg})^2 +
\]

\[
\mu (1 + \mu^2 N(X))^{1/2} \nabla (X^+ \nabla^+ - \tilde{\deg})^2 + \mu^2 (X^+ \nabla^+ - \tilde{\deg})^2 +
\]

\[
(1 + \mu^2 N(X))^{1/2} \nabla (1 + \mu^2 N(X))^{1/2} \nabla^+ (X^+ \nabla^+ - \tilde{\deg})
\]

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and then work out each entry separately. By (50) and (52), the diagonal terms are
\[
\mu^2(\deg^2 - N(X)\Box) + (1 + \mu^2N(X))\Box + \mu^2X\nabla = \Box + \mu^2(\deg^2 + X\nabla),
\]
\[
\mu^2(\deg^2 - N(X)\Box) + (1 + \mu^2N(X))\Box + \mu^2X^+\nabla^+ = \Box + \mu^2(\deg^2 + X^+\nabla^+).
\]

By (46), (50) and (51), the off-diagonal terms are
\[
\mu(X\nabla - \text{deg})(1 + \mu^2N(X))^{1/2}X^+ + \mu(1 + \mu^2N(X))^{1/2}(X^+\nabla^+ - \text{deg}) = \mu(1 + \mu^2N(X))^{1/2}X^+X^+\nabla^+ - \text{deg}) = \mu(1 + \mu^2N(X))^{1/2}X^+\nabla^+
\]

and similarly
\[
\mu(X^+\nabla^+ - \text{deg})(1 + \mu^2N(X))^{1/2}\nabla + \mu(1 + \mu^2N(X))^{1/2}\nabla(X\nabla - \text{deg}) = \mu(1 + \mu^2N(X))^{1/2}(X^+\nabla - \text{deg})X\nabla = \mu(1 + \mu^2N(X))^{1/2}\nabla.
\]

This proves \(\nabla_\mu^2 = \Box_\mu + \mu\nabla_\mu.\)

The two equations (51) can be combined into a single equation as
\[
\begin{pmatrix}
0 & \nabla^+ \\
\nabla & 0
\end{pmatrix}
\begin{pmatrix}
0 & X^+ \\
X^+ & 0
\end{pmatrix}
+ \begin{pmatrix}
0 & \nabla^+ \\
\nabla & 0
\end{pmatrix}
\begin{pmatrix}
0 & X^+ \\
X^+ & 0
\end{pmatrix}
= 2 \begin{pmatrix}
\deg^2 + 2 & 0 \\
0 & \deg + 2
\end{pmatrix} = 2(\deg + 2).
\]

In our context this formula becomes
\[
(\nabla_\mu - \mu)\begin{pmatrix}
0 & X^+ \\
X^+ & 0
\end{pmatrix} + \begin{pmatrix}
0 & X^+ \\
X^+ & 0
\end{pmatrix} \nabla_\mu = 2(1 + \mu^2N(X))^{1/2}(\deg + 2).
\]

We introduce another operator, \(\nabla_\mu\), which we apply to functions on the right:
\[
\nabla_\mu : (g_1, g_2) \mapsto (g_1, g_2) \begin{pmatrix}
\mu(\text{deg} - \nabla^+X^+) & \nabla^+(1 + \mu^2N(X))^{1/2} \\
\nabla((1 + \mu^2N(X))^{1/2} & \mu(\text{deg} - \nabla X)
\end{pmatrix}
\]
\[
= \begin{pmatrix}
\mu(\text{deg}g_1 - (g_1\nabla^+)X^+) + (1 + \mu^2N(X))^{1/2}(g_2\nabla) \\
(1 + \mu^2N(X))^{1/2}(g_1\nabla^+) + \mu(\text{deg}g_2 - (g_2\nabla)X)
\end{pmatrix}.
\]

**Proposition 35.** We have a factorization
\[
\Box_\mu = \nabla_\mu(\Box_\mu + \mu).
\]

**Remark 36.** One can produce functions satisfying \(\nabla_\mu f = 0\) and \(g\nabla_\mu = 0\) as follows. Start with a \(\mathbb{C}\)-valued function \(\varphi\) annihilated by \(\Box_\mu\) (for example, take \(\varphi \in \mathcal{H}_\mu\)). Then the two columns of \((\nabla_\mu - \mu)\varphi\) satisfy \(\nabla_\mu f = 0\) and the two rows of \(\varphi(\nabla_\mu + \mu)\) satisfy \(g\nabla_\mu = 0\).

### 15 Basic Properties of Regular Functions

Recall from [FL1] that
\[
Dx = dx^1 \wedge dx^2 \wedge dx^3 - idx^0 \wedge dx^2 \wedge dx^3 + jdx^0 \wedge dx^1 \wedge dx^3 - kdx^0 \wedge dx^1 \wedge dx^2
\]

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is an $\mathbb{H}$-valued 3-form on $\mathbb{H}$ that is Hodge dual to

$$dX = dx^0 + idx^1 + jdx^2 + kdx^3.$$  

We also introduce

$$Dx^+ = dx^1 \wedge dx^2 \wedge dx^3 + idx^0 \wedge dx^2 \wedge dx^3 - jdx^0 \wedge dx^1 \wedge dx^3 + kdx^0 \wedge dx^1 \wedge dx^2,$$

which is Hodge dual to

$$dX^+ = dx^0 - idx^1 - jdx^2 - kdx^3$$

and

$$Dr = x^0 dx^1 \wedge dx^2 \wedge dx^3 - x^1 dx^0 \wedge dx^2 \wedge dx^3 + x^2 dx^0 \wedge dx^1 \wedge dx^3 - x^3 dx^0 \wedge dx^1 \wedge dx^2,$$

which is Hodge dual to

$$dr = x^0 dx^0 + x^1 dx^1 + x^2 dx^2 + x^3 dx^3.$$  

Recall that $dV = dx^0 \wedge dx^1 \wedge dx^2 \wedge dx^3$ is the volume form on $\mathbb{H}$. If $f = (f_1)$ and $g = (g_1, g_2)$ are two functions defined on an open set in $\mathbb{H}$, then

$$d(Dx \cdot f) = (\nabla^+ f)dV, \quad d(Dx^+ \cdot f) = (\nabla f)dV, \quad d(f \cdot Dr) = (\deg f + 4f)dV, \quad d(g \cdot Dx) = (g\nabla)dV, \quad d(g \cdot Dx^+) = (g\nabla)dV.$$

Note that

$$Dr = \frac{1}{2} (X \cdot Dx^+ + Dx \cdot X^+) = \frac{1}{2} (X^+ \cdot Dx + Dx^+ \cdot X).$$

Consider a matrix-valued 3-form on $\mathbb{H}$

$$Dx_\mu = \begin{pmatrix} \mu X \cdot Dx^+ - Dr \\ (1 + \mu^2 N(X))^{1/2} \end{pmatrix} = \begin{pmatrix} \mu X \cdot Dx^+ - Dr \\ (1 + \mu^2 N(X))^{1/2} \end{pmatrix}.$$  

Lemma 37.

$$d(g \cdot Dx_\mu \cdot f) = (1 + \mu^2 N(X))^{-1/2} ((g\overline{\nabla}_\mu)f + g(\nabla f))dV.$$  

Proof. Using

$$[X\nabla - \deg (1 + \mu^2 N(X))] = [X^+\nabla^+ - \deg (1 + \mu^2 N(X))] = 0,$$

we compute the components of $d(g \cdot Dx_\mu \cdot f)$ coming from the diagonal entries of $Dx_\mu$:

$$d(g_1 (X \cdot Dx^+ - Dx \cdot X^+) f_1) = \left( ((g_1 X) \nabla - (g_1 \nabla^+) X^+) \cdot f_1 + g_1 \cdot (X(\nabla f_1) - \nabla^+ (X^+ f_1)) \right) dV$$

$$= 2 \left( (\deg g_1 - (g_1 \nabla^+) X^+) \cdot f_1 + g_1 \cdot (X(\nabla f_1) - \deg f_1) \right) dV,$$

$$d(g_2 (X^+ \cdot Dx - Dx^+ \cdot X) f_2) = \left( ((g_2 X^+) \nabla^+ - (g_2 \nabla) X) \cdot f_2 + g_2 \cdot (X^+(\nabla^+ f_2) - \nabla (X f_2)) \right) dV$$

$$= 2 \left( (\deg g_2 - (g_2 \nabla) X) \cdot f_2 + g_2 \cdot (X^+(\nabla^+ f_2) - \deg f_2) \right) dV.$$

Then the result follows.

As an immediate consequence we obtain Cauchy’s integral theorem:
Corollary 38. Let \( f = \left( \frac{f_1}{f_2} \right) \) and \( g = (g_1, g_2) \) be two functions defined on an open set \( U \subset \mathbb{H} \) such that \( \nabla_\mu f = 0 \) and \( g \cdot \nabla_\mu = 0 \). Then \( g \cdot D\mu : f \) is a closed 3-form. In particular, if \( C \) is a 3-cycle in \( U \) (with compact support), then the integral \( \int_C g \cdot D\mu : f \) depends only on the homology class of \( C \).

Lemma 39. Let \( a, d \in \mathbb{H} \) with \( N(a) = N(d) = 1 \), then the pull-back of \( D\mu \) under the map \( X \mapsto aXd^{-1} \) is
\[
\begin{pmatrix} a & 0 \\ 0 & d \end{pmatrix} D\mu \begin{pmatrix} a & 0 \\ 0 & d \end{pmatrix}^{-1}.
\]

Lemma 40. Let \( f = \left( \frac{f_1}{f_2} \right) \) be a left-regular function (i.e. satisfying \( \nabla_\mu f = 0 \)). Then so is
\[
\begin{pmatrix} a^{-1}f_1(aXd^{-1}) \\ d^{-1}f_2(aXd^{-1}) \end{pmatrix}, \quad \text{for any } a, d \in \mathbb{H} \text{ with } N(a) = N(d) = 1.
\]

Proof. Using
\[
\nabla(a^{-1}f_1(aXd^{-1})) = d^{-1}(\nabla f_1)|_{aXd^{-1}} \quad \text{and} \quad \nabla^+(d^{-1}f_2(aXd^{-1})) = a^{-1}(\nabla^+ f_2)|_{aXd^{-1}},
\]
we compute
\[
\nabla_\mu \begin{pmatrix} a^{-1}f_1(aXd^{-1}) \\ d^{-1}f_2(aXd^{-1}) \end{pmatrix} = \begin{pmatrix} a & 0 \\ 0 & d \end{pmatrix}^{-1} \nabla_\mu \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}|_{aXd^{-1}} = 0.
\]

16 Analogue of the Cauchy-Fueter Formula

The Cauchy-Fueter kernel in our setting is
\[
k_\mu(X,Y) = -\frac{1}{2} K_\mu(X,Y)(\nabla_\mu + \mu).
\]

If \( U \subset \mathbb{H} \) is an open region with piecewise \( C^1 \) boundary \( \partial U \), we define a preferred orientation on \( \partial U \) as follows. The positive orientation of \( U \) is determined by the vectors \( \{1, i, j, k\} \) (or the volume form \( dV \)). Pick a non-singular point \( p \in \partial U \) and let \( \overrightarrow{p} \) be a non-zero vector in \( T_p \mathbb{H} \) perpendicular to \( T_p \partial U \) and pointing outside of \( U \). Then \( \{\overrightarrow{1}, \overrightarrow{2}, \overrightarrow{3}\} \subset T_p \partial U \) is positively oriented in \( \partial U \) if and only if \( \{\overrightarrow{p}, \overrightarrow{1}, \overrightarrow{2}, \overrightarrow{3}\} \) is positively oriented in \( \mathbb{H} \). Now we can prove our analogue of the Cauchy-Fueter formula:

Theorem 41. Let \( U \subset \mathbb{H} \) be an open bounded subset with piecewise \( C^1 \) boundary \( \partial U \). Suppose that \( f(X) \) is left-regular on a neighborhood of the closure \( \overline{U} \) (i.e. satisfying \( \nabla_\mu f = 0 \)), then
\[
\frac{1}{2\pi^2} \int_{\partial U} k_\mu(X,Y) \cdot D\mu : f(X) = \begin{cases} f(Y) & \text{if } Y \in U; \\ 0 & \text{if } Y \notin \overline{U}. \end{cases}
\]

Remark 42. There is a similar formula for right-regular functions (i.e. functions satisfying \( g \nabla_\mu = 0 \)). The Cauchy-Fueter kernel in that case is \( k'_\mu(X,Y) = -\frac{1}{2}(\nabla_\mu - \mu)K_\mu(X,Y) \).

Proof. By Remark 36 and Corollary 38 the integrand is a closed 3-form. If \( Y \notin \overline{U} \), by Corollary 38 the integral is zero. So let us assume \( Y \in U \). Consider a sphere \( S^2_\varepsilon(Y) \) of radius \( \varepsilon \) centered at \( Y \), and let \( \varepsilon \) be small enough so that the closed ball of radius \( \varepsilon \) centered at \( Y \) lies inside \( U \). Then
\[
\int_{\partial U} k_\mu(X,Y) \cdot D\mu : f(X) = \int_{S^2_\varepsilon(Y)} k_\mu(X,Y) \cdot D\mu : f(X).
\]
The right hand side is independent from \( \varepsilon \) and it is sufficient to show that

\[
\lim_{\varepsilon \to 0^+} \int_{S^2(Y)} k_\mu(X, Y) \cdot D x_\mu \cdot f(X) = 2\pi^2 \cdot f(Y).
\]

We compute

\[
k_\mu(X, Y) \cdot ((\dot{X} - \dot{Y}, X - \dot{Y})_{1,4})^2
= \left( \frac{\mu Y X^+}{X^+ \sqrt{1 + \mu^2 N(Y)}} - \frac{Y^+ \sqrt{1 + \mu^2 N(X)}}{\mu Y^+} \right) X \sqrt{1 + \mu^2 N(Y)} - Y \sqrt{1 + \mu^2 N(X)} + 2\mu^{-1} + \frac{\mu}{2} \text{Tr}(X Y^+) - 2\mu^{-1} \sqrt{1 + \mu^2 N(X)} \cdot \sqrt{1 + \mu^2 N(Y)}.
\]

Let \( X' = X - Y \), then \( N(X') = \varepsilon^2 \) and by Lemma 6 of [FL1]

\[
D x_\mu|_{S^2(Y)} = \left( \frac{\mu X X' + X' X}{2 \sqrt{1 + \mu^2 N(X)}} \right) \frac{X'}{X'} \left( \frac{\mu X X' - X' X}{2 \sqrt{1 + \mu^2 N(X)}} \right) \frac{dS}{\varepsilon}.
\]

To simplify upcoming expressions, we introduce a notation \( b = \sqrt{1 + \mu^2 N(Y)} \). Working with the lowest order terms with respect to \( X' \) and ignoring the higher order terms we get:

\[
f(X) \sim f(Y), \quad ((\dot{X} - \dot{Y}, X - \dot{Y})_{1,4})^2 \sim \varepsilon^4 \cdot \left( 1 - \frac{\mu^2}{4\varepsilon^2 b^2} (\text{Tr}(X Y^+))^2 \right) \cdot \left( \frac{\mu Y X' + X' Y}{2 \sqrt{1 + \mu^2 N(X)}} \right) \frac{X'}{X'} \left( \frac{\mu X X' - X' X}{2 \sqrt{1 + \mu^2 N(X)}} \right) \frac{dS}{\varepsilon},
\]

\[
k_\mu(X, Y) \sim \varepsilon^{-4} \cdot \left( 1 - \frac{\mu^2}{4\varepsilon^2 b^2} (\text{Tr}(X Y^+))^2 \right) \cdot \left( \frac{\mu Y X' + X' Y}{2 \sqrt{1 + \mu^2 N(X)}} \right) \frac{X'}{X'} \left( \frac{\mu X X' - X' X}{2 \sqrt{1 + \mu^2 N(X)}} \right) \frac{dS}{\varepsilon}.
\]

Using Lemma 40 we can assume that \( Y \) is real. Then

\[
D x_\mu|_{S^2(Y)} = \varepsilon^{-1} \cdot \left( \frac{-\mu Y \cdot \text{Im}(X')}{X'} \right) \frac{X'}{X'} \left( \frac{\mu Y \cdot \text{Im}(X')}{X'} \right) \frac{dS}{\varepsilon},
\]

\[
k_\mu(X, Y) \sim \varepsilon^{-4} \cdot \left( 1 - \frac{\mu^2 Y^2}{\varepsilon^2 b^2} (\text{Re}(X'))^2 \right) \cdot \left( \frac{-\mu Y \cdot \text{Im}(X')}{X'} \right) \frac{X'}{X'} \left( \frac{\mu Y \cdot \text{Im}(X')}{X'} \right),
\]

\[
k_\mu(X, Y) \cdot D x_\mu|_{S^2(Y)} \sim \varepsilon^{-5} \cdot \left( 1 - \frac{\mu^2 Y^2}{\varepsilon^2 b^2} (\text{Re}(X'))^2 \right) \cdot \left( \varepsilon^2 b + \frac{\mu^2 Y^2}{b} \left( (\text{Im}(X'))^2 - (\text{Re}(X'))^2 \right) \right) \frac{dS}{\varepsilon},
\]

\[
+ \varepsilon^{-5} \cdot \left( 1 - \frac{\mu^2 Y^2}{\varepsilon^2 b^2} (\text{Re}(X'))^2 \right) \cdot \frac{\mu^2 Y^2}{b^2} \text{Re}(X') \cdot \text{Im}(X') \left( \frac{b}{\mu Y} - \frac{-\mu Y}{-b} \right) \frac{dS}{\varepsilon}.
\]

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The integral over $S^3_\varepsilon(Y)$ of the last term is zero, and the first term simplifies to

$$
\varepsilon^{-3} b^{-1} \left(1 - \frac{\mu^2 Y^2}{\varepsilon^2 b^2} (\Re(X'))^2 \right)^{-2} dS.
$$

We finish the proof by integrating in spherical coordinates and using an integral

$$
\int_{\theta=-\pi/2}^{\theta=\pi/2} \frac{\sin^2 \theta \, d\theta}{(1 - a \cos^2 \theta)^2} = \frac{\pi}{2\sqrt{1 - a}}, \quad |a| < 1,
$$

with $a = \mu^2 Y^2 b^{-2}$.

## 17 Deformation of $\mathcal{K}$ and the Second Order Pole

Similarly to how we did in Section 12, we introduce a space of functions $\mathcal{K}_\mu$, which is a deformation of $\mathcal{K}$. Then we discuss the analogues of the second order pole formulas given in Corollary 14 and Theorem 15. Thus we introduce a vector space

$$
\mathcal{K}_\mu = \mathbb{C}\text{-span of } \frac{t_{m,n}^l(X) \cdot ((1 + \mu^2 N(X))^{1/2} - 1)^k}{((1 + \mu^2 N(X))^{1/2} + 1)^{2l+k+2}}, \quad k \in \mathbb{Z}, \quad l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots,
$$

$$
m, n = -l, -l + 1, \ldots, l.
$$

Note that when $\mu \to 0$,

$$
2^{2l+2k+2} \mu^{-2k} \frac{t_{m,n}^l(X) \cdot ((1 + \mu^2 N(X))^{1/2} - 1)^k}{((1 + \mu^2 N(X))^{1/2} + 1)^{2l+k+2}} \to t_{m,n}^l(X) \cdot N(X)^k.
$$

We can extend these functions to an open neighborhood of $\mathbb{H}_\kappa$ in $\mathbb{H}_\kappa$ as follows. (We exclude $Z \in \mathbb{H}_\kappa$ such that $N(Z) = 0$ because $(1 + \mu^2 N(X))^{1/2} - 1$ vanishes there.) The matrix coefficient functions $t_{m,n}^l(X)$’s are polynomials in $X$, hence extend to $\mathbb{H}_\kappa$ without any problem. The only obstacle to extending the functions spanning $\mathcal{K}_\mu$ is the square root in $(1 + \mu^2 N(X))^{1/2} \pm 1$. Thus we choose the branch of $z^{1/2}$ defined on the complex plane without the negative real axis and observe that the functions

$$
f_{k,l,m,n}(Z) = \frac{t_{m,n}^l(Z) \cdot ((1 + \mu^2 N(Z))^{1/2} - 1)^k}{((1 + \mu^2 N(Z))^{1/2} + 1)^{2l+k+2}}, \quad Z \in \mathbb{H}_\kappa,
$$

are well defined as long as $N(Z) \notin (-\infty, -\mu^{-2}]$ and $N(Z) \neq 0$. For this reason we introduce an open region in $\mathbb{H}_\kappa$

$$
U_\mu = \{Z \in \mathbb{H}_\kappa; \ N(Z) \notin (-\infty, -\mu^{-2}]\}.
$$

Our next task is to define a natural bilinear pairing on $\mathcal{K}_\mu$. Fix an $R > 0$ and parameterize $U(2)_R$ as in Chapter III, §1, of [V]:

\[
Z(\alpha, \varphi, \theta, \psi) = Re^{i\alpha} \begin{pmatrix} e^{i\frac{\varphi}{2}} & 0 & e^{-i\frac{\varphi}{2}} \\ 0 & \cos \theta & i \sin \theta \\ e^{i\frac{\varphi}{2}} & i \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} e^{i\frac{\psi}{2}} & 0 & e^{-i\frac{\psi}{2}} \\ 0 & e^{i\frac{\psi}{2}} & -i \sin \theta \\ e^{-i\frac{\psi}{2}} & i \sin \theta & e^{-i\frac{\psi}{2}} \end{pmatrix}, \quad 0 \leq \alpha < \pi, \quad 0 \leq \varphi < 2\pi, \quad 0 \leq \theta < \pi, \quad -2\pi \leq \psi < 2\pi.
\]
By direct computation we find
\[
dV_{U(2)R} = dz^0 \wedge dz^1 \wedge dz^2 \wedge dz^3\bigg|_{U(2)R} = \frac{1}{4} d\zeta_{11} \wedge d\zeta_{12} \wedge d\zeta_{21} \wedge d\zeta_{22}\bigg|_{U(2)R} = \frac{R^4}{8t} e^{4i\alpha} \sin \theta \, d\sigma \wedge d\varphi \wedge d\theta \wedge d\psi.
\]
For \(0 < R < \mu^{-1}\), define a measure on \(U(2)R\) by
\[
dV_{R,\mu} = \frac{R^4}{16} e^{4i\alpha} \sin \theta \, d\varphi \wedge d\theta \wedge d\psi \wedge d\log\left(\frac{(1 + \mu^2 R^2 e^{2i\alpha})^{1/2} - 1}{(1 + \mu^2 R^2 e^{2i\alpha})^{1/2} + 1}\right)
\]
and define a bilinear pairing on \(\mathcal{K}_\mu\) as
\[
\langle f_1, f_2 \rangle_\mu = \frac{i}{2\pi^3} \int_{Z \in U(2)R} f_1(Z) \cdot f_2(Z) \, dV_{R,\mu}, \quad f_1, f_2 \in \mathcal{K}_\mu.
\]  
(The parameter \(R\) is restricted to \(0 < R < \mu^{-1}\) so that \(U(2)R \subset U_\mu\).) We have the following analogue of the orthogonality relations (19):

**Proposition 43.** The symmetric pairing (53) is independent of the choice of \(R\) (as long as \(0 < R < \mu^{-1}\)) and non-degenerate. Let
\[
f'_{k,l,m,n}(Z) = \frac{t_{m,n}(Z^+) \cdot \left((1 + \mu^2 N(Z))^{1/2} + 1\right)^{k'}}{\left((1 + \mu^2 N(Z))^{1/2} - 1\right)^{2l+k+2}} \in \mathcal{K}_\mu,
\]
then we have orthogonality relations
\[
\langle f_{k,l,m,n}(Z), f'_{k',l',m',n'}(Z) \rangle_\mu = \frac{\mu^{-4l-4}}{2l+1} \delta_{kk'} \delta_{ll'} \delta_{mm'} \delta_{nn'},
\]  
where the indices \(k, l, m, n\) are \(k \in \mathbb{Z}, \ l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots, \ m, n \in \mathbb{Z} + l, \ -l \leq m, n \leq l\) and similarly for \(k', l', m', n'\).

**Proof.** Since each family of functions \(f_{k,l,m,n}(Z)\)'s and \(f'_{k,l,m,n}(Z)\)'s generates \(\mathcal{K}_\mu\), the independence of \(R\) and non-degeneracy of the bilinear pairing follow from the orthogonality relations (54). Using the orthogonality relations (17), we obtain
\[
-2\pi^3 i \cdot \langle f_{k,l,m,n}(Z), f'_{k',l',m',n'}(Z) \rangle_\mu = \int_{Z \in U(2)R} \frac{t_{m,n}(Z) \cdot \left((1 + \mu^2 N(Z))^{1/2} - 1\right)^k \cdot t_{m',n'}(Z^+) \cdot \left((1 + \mu^2 N(Z))^{1/2} + 1\right)^{k'}}{\left((1 + \mu^2 N(Z))^{1/2} + 1\right)^{2l+k+2} \cdot \left((1 + \mu^2 N(Z))^{1/2} - 1\right)^{2l+k'+2}} \, dV_{R,\mu}
\]
\[
= \int \frac{\mu^{-4l} \cdot t_{m,n}(Z) \cdot t_{m',n'}(Z^+) \cdot N(Z)^{-2}}{\left((1 + \mu^2 N(Z))^{1/2} + 1\right)^{2l} \cdot \left((1 + \mu^2 N(Z))^{1/2} - 1\right)^{2l}} \cdot \frac{\left((1 + \mu^2 N(Z))^{1/2} - 1\right)^{k-k'}}{\left((1 + \mu^2 N(Z))^{1/2} + 1\right)^{k'}} \, dV_{R,\mu}
\]
\[
= -2\pi^3 i \frac{\mu^{-4l-4}}{2l+1} \delta_{ll'} \delta_{mm'} \delta_{nn'} \int_{0}^{\alpha=\pi} \frac{\left((1 + \mu^2 R^2 e^{2i\alpha})^{1/2} - 1\right)^{k-k'}}{\left((1 + \mu^2 R^2 e^{2i\alpha})^{1/2} + 1\right)} \, d\log\left(\frac{(1 + \mu^2 R^2 e^{2i\alpha})^{1/2} - 1}{(1 + \mu^2 R^2 e^{2i\alpha})^{1/2} + 1}\right)
\]
\[
= -2\pi^3 i \frac{\mu^{-4l-4}}{2l+1} \delta_{ll'} \delta_{mm'} \delta_{nn'} \int z^{k-k'-1} \, dz = -2\pi^3 i \frac{\mu^{-4l-4}}{2l+1} \delta_{kk'} \delta_{ll'} \delta_{mm'} \delta_{nn'},
\]
\[
\square
\]
Let us recall Proposition 27 from [FL1] restated here as Proposition 10. We want to obtain a similar expansion for $(⟨\hat{X} – \hat{Y}, \hat{X} – \hat{Y}⟩)_{1,1}$, $t_1 = \sqrt{1 + \mu^2 N(X)}$, $t_2 = \sqrt{1 + \mu^2 N(Y)} \in \mathbb{C}$ and choose $\theta_1, \theta_2 \in \mathbb{C}$ so that
\[
\cosh \theta_1 = t_1 = \sqrt{1 + \mu^2 N(X)} \quad \text{and} \quad \cosh \theta_2 = t_2 = \sqrt{1 + \mu^2 N(Y)}.
\]
(The square roots $\sqrt{1 + \mu^2 N(X)}$ and $\sqrt{1 + \mu^2 N(Y)}$ are uniquely defined, but $\theta_1$ and $\theta_2$ are not.) Then $\sinh^2 \theta_1 = \mu^2 N(X)$ and $\sinh^2 \theta_2 = \mu^2 N(Y)$. Define
\[
\hat{u} = \frac{\mu X}{\sinh \theta_1}, \quad \hat{v} = \frac{\mu Y}{\sinh \theta_2} \in \mathbb{H}_\mathbb{C},
\]
and suppose that $\hat{u} \hat{v}^{-1}$ is similar to a diagonal matrix $\begin{pmatrix} \lambda & 0 \\ 0 & \lambda^{-1} \end{pmatrix}$, where $\lambda \in \mathbb{C}$. Using the multiplicativity property of matrix coefficients (15) and our previous notations (48), we compute a sum over all $m, n = -l, -l + 1, \ldots, l$, then over $k = 0, 1, 2, 3, \ldots$ and $l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots$:
\[
\sum_{k,l,m,n} (2l + 1)\mu^{4l+4} f_{k,l,m,n}(X) \cdot f'_{k,l,m,n}(Y)
\]
\[
= \mu^4 \sum_{k,l} (2l + 1) \frac{(t_1 - 1)^{l+k}}{(t_1 + 1)^{l+k+2}} \cdot \frac{(t_2 + 1)^{l+k}}{(t_2 - 1)^{l+k+2}} \cdot \chi_l(\hat{u}, \hat{v})^{-1}
\]
\[
= \frac{16\mu^4(\lambda - \lambda^{-1})^{-1}}{(e^{\theta_1} + e^{-\theta_1} + 1)^2(e^{\theta_2} + e^{-\theta_2} - 2)^2} \sum_{k,l} (2l + 1) \frac{b^{2l+2k}}{a^{2l+2k}} \cdot (\lambda^{2l+1} - \lambda^{-2l+1})
\]
\[
= \frac{16\mu^4(\lambda - \lambda^{-1})^{-1}}{(e^{\theta_1/2} + e^{-\theta_1/2})^4(e^{\theta_2/2} - e^{-\theta_2/2})^4(1 - b^2/a^2)} \sum_{l} (2l + 1) \frac{b^{2l}}{a^{2l}} \cdot (\lambda^{2l+1} - \lambda^{-2l+1})
\]
\[
= \frac{16\mu^4}{(a - \lambda b)^2(a - \lambda^{-1}b)^2} = \frac{16\mu^4}{N^2(b \hat{u} - a \hat{v})} = \frac{1}{(⟨\hat{X} – \hat{Y}, \hat{X} – \hat{Y}⟩)_{1,1}^2} (55)
\]
where in the last step we used (49) and
\[
\hat{X} = (\sqrt{\mu^2 + N(X)}, x^0, x^1, x^2, x^3) \quad \text{and} \quad \hat{Y} = (\sqrt{\mu^2 + N(Y)}, y^0, y^1, y^2, y^3) \in \mathbb{R}_{1,4}.
\]
Like the expansion of $⟨\hat{X} – \hat{Y}, \hat{X} – \hat{Y}⟩^{-1}$, this expansion holds whenever
\[
|\lambda b/a| < 1 \quad \text{and} \quad |\lambda^{-1}b/a| < 1
\]
and, in particular, for those $X, Y$ the denominator does not turn to zero.

We avoid finding the region where these inequalities are satisfied and impose instead an assumption that $|\lambda| = 1$. We have:
\[
\frac{b^2}{a^2} = \frac{\tan^2(\theta_1/2)}{\tan^2(\theta_2/2)} = \frac{t_1 - 1}{t_1 + 1} \frac{t_2 + 1}{t_2 - 1} = \frac{\sqrt{1 + \mu^2 N(X)} - 1}{\sqrt{1 + \mu^2 N(X)} + 1} \frac{\sqrt{1 + \mu^2 N(Y)} + 1}{\sqrt{1 + \mu^2 N(Y)} - 1}.
\]
Thus the expansion (55) certainly holds for $X, Y \in \mathbb{U}_\mu$ such that $XY^{-1}$ is diagonalizable with both eigenvalues having the same length and
\[
\frac{|\sqrt{1 + \mu^2 N(X)} - 1|}{\sqrt{1 + \mu^2 N(X)} + 1} < \frac{|\sqrt{1 + \mu^2 N(Y)} - 1|}{\sqrt{1 + \mu^2 N(Y)} + 1}.
\]
The condition that $XY^{-1}$ is diagonalizable with both eigenvalues having the same length is automatically satisfied if $X \in U(2)_{R_1}$ and $Y \in U(2)_{R_2}$.

Using single variable calculus, we can prove:

**Lemma 44.** Let $0 < R < \mu^{-1}$. Then, as $X$ ranges over $U(2)_R$,

$$\frac{\sqrt{1 + \mu^2 R^2} - 1}{\sqrt{1 + \mu^2 R^2} + 1} \leq \frac{\sqrt{1 + \mu^2 N(X)} - 1}{\sqrt{1 + \mu^2 N(X)} + 1} \leq \frac{1 - \sqrt{1 - \mu^2 R^2}}{1 + \mu^2 R^2 + 1}.$$  

Define subspaces of $\mathcal{H}_\mu$ similar to $\mathcal{H}^+, \mathcal{H}^-$ and $\mathcal{H}^0$:

\[ \mathcal{H}_\mu^+ = C - \text{span of } \{f_{k,l,m,n}(Z); k \geq 0\}, \]
\[ \mathcal{H}_\mu^- = C - \text{span of } \{f_{k,l,m,n}(Z); k \leq -(2l + 2)\}, \]
\[ \mathcal{H}_\mu^0 = C - \text{span of } \{f_{k,l,m,n}(Z); -(2l + 1) \leq k \leq -1\} \]

(and the ranges of indices $l, m, n$ are $l = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots$, $m, n = -l, -l+1, \ldots, l$, as before). Thus $\mathcal{H}_\mu = \mathcal{H}_\mu^- \oplus \mathcal{H}_\mu^0 \oplus \mathcal{H}_\mu^+$.

**Remark 45.** The spaces $\mathcal{H}_\mu^+$, $\mathcal{H}_\mu^-$, $\mathcal{H}_\mu^0$ and $\mathcal{H}_\mu^+$ are defined by analogy with spaces $\mathcal{H}_\mu$ and $\mathcal{H} = \mathcal{H}^- \oplus \mathcal{H}^0 \oplus \mathcal{H}^+$. We believe that these spaces can be characterized as images under the multiplication maps on $\mathcal{H}_\mu^+ \otimes \mathcal{H}_\mu^+$. Thus $\mathcal{H}_\mu^-$, $\mathcal{H}_\mu^-, \mathcal{H}_\mu^0$ and $\mathcal{H}_\mu^+$ should be the images of $\mathcal{H}_\mu \otimes \mathcal{H}_\mu^-$, $\mathcal{H}_\mu^- \otimes \mathcal{H}_\mu^-$, $\mathcal{H}_\mu^- \otimes \mathcal{H}_\mu^+$ and $\mathcal{H}_\mu^+ \otimes \mathcal{H}_\mu^+$ respectively. (Compare with Lemma 8.)

Note that $\mathcal{H}_\mu^- = C - \text{span of } \{f_{k,l,m,n}(Z); k \geq 0\}$.

From our expansion of $(\langle \hat{X} - \hat{Y}, \hat{X} - \hat{Y} \rangle_{1,4})^{-2}$ we immediately obtain the following analogue of Corollary 14:

**Proposition 46.** Let $0 < R < \mu^{-1}$ and $r > 0$.

1. If $Y \in U(2)_r$ and

\[ \frac{\sqrt{1 + \mu^2 N(Y)} - 1}{\sqrt{1 + \mu^2 N(Y)} + 1} \leq \frac{\sqrt{1 + \mu^2 R^2} - 1}{\sqrt{1 + \mu^2 R^2} + 1}, \]

then $r < R$ and the map

\[ f \mapsto (P^+_\mu f)(Y) = \frac{i}{2\pi^3} \int_{X \in U(2)_R} \frac{f(X) dV_{R,\mu}}{(\langle \hat{X} - \hat{Y}, \hat{X} - \hat{Y} \rangle_{1,4})^2}, \quad f \in \mathcal{H}_\mu^+, \]

is a projector onto $\mathcal{H}_\mu^+$ annihilating $\mathcal{H}_\mu^- \oplus \mathcal{H}_\mu^0$ and, in particular, provides a reproducing formula for functions in $\mathcal{H}_\mu^+$;

2. If $Y \in U(2)_r \cap \mathbb{U}_\mu$ and

\[ \frac{1 - \sqrt{1 - \mu^2 R^2}}{\sqrt{1 - \mu^2 R^2} + 1} \leq \frac{\sqrt{1 + \mu^2 N(Y)} - 1}{\sqrt{1 + \mu^2 N(Y)} + 1}, \]

then $r > R$ and the map

\[ f \mapsto (P^-_\mu f)(Y) = \frac{i}{2\pi^3} \int_{X \in U(2)_R} \frac{f(X) dV_{R,\mu}}{(\langle \hat{X} - \hat{Y}, \hat{X} - \hat{Y} \rangle_{1,4})^2}, \quad f \in \mathcal{H}_\mu^-, \]

is a projector onto $\mathcal{H}_\mu^-$ annihilating $\mathcal{H}_\mu^0 \oplus \mathcal{H}_\mu^+$ and, in particular, provides a reproducing formula for functions in $\mathcal{H}_\mu^-$. 

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The reproducing kernel and projector for the space $\mathcal{K}_\mu^0$ can be obtained formally as in Section 5 and with full rigor as in Section 6. The advantage of the anti de Sitter deformation of $\mathcal{K}_\mu^0$ (and also $\mathcal{K}_\mu^\pm$) is that now we can extend the functions from this representation to the ambient five-dimensional Minkowski space $\mathbb{R}^{1,4}$, and we expect some additional flexibility in the permissible choices of integration cycles for the quaternionic analogues of Cauchy’s formula for the second order pole (cf. Theorem 15 in this paper for the scalar case and Theorem 77 in [FL1] for the spinor case).

References


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