BURGHELEA-FRIEDLANDER-KAPPELER’S GLUING FORMULA
FOR THE ZETA-DETERMINANT AND ITS APPLICATIONS
TO THE ADIABATIC DECOMPOSITIONS OF THE
ZETA-DETERMINANT AND THE ANALYTIC TORSION

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ABSTRACT. The gluing formula of the zeta-determinant of a Laplacian given
by Burghelea, Friedlander and Kappeler contains an unknown constant. In this
paper we compute this constant to complete the formula under an assumption
that the product structure is given near the boundary. As applications of this
result, we prove the adiabatic decomposition theorems of the zeta-determinant
of a Laplacian with respect to the Dirichlet and Neumann boundary conditions
and of the analytic torsion with respect to the absolute and relative boundary
conditions.

1. Introduction

In [3], Burghelea, Friedlander and Kappeler established a gluing formula for the
zeta determinant of an elliptic operator on a compact manifold. This formula con-
tains an unknown constant which can be expressed in terms of the zero coefficients
of some asymptotic expansions. In this paper we compute this constant in the case
when the product structure is given near the boundary, and then we apply this
result to prove the adiabatic decomposition theorems for the zeta determinant and
the analytic torsion. Some results of this paper are known from the work of Klimek
and Wojciechowski in [6], but our method is completely different from theirs.

Let $M$ be a compact oriented $m$-dimensional manifold with boundary $Z$ ($Z$ may
be empty), and $Y$ a hypersurface of $M$ such that $M - Y$ has two components
and $Y \cap Z = \emptyset$. We denote by $M_1$, $M_2$ the closure of each component, i.e. $M = M_1 \cup_Y M_2$. Choose a collar neighborhood $N$ of $Y$, which is diffeomorphic to $[-1,1] \times Y$, $N \cap Z = \emptyset$, and choose a metric $g$ on $M$ that is a product metric on $N$. Suppose that $E \to M$ is a complex vector bundle such that $E|_N$ has the product structure, which
means that $E|_N = p^* E|_Y$, where $p : [-1,1] \times Y \to Y$ is the canonical projection.
Let $\Delta_M$ be a Laplacian acting on smooth sections of $E$, and let $\Delta_{M_1}, \Delta_{M_2}$ be the
restrictions of $\Delta_M$ to $M_1$ and $M_2$. By a Laplacian we mean a positive semi-definite
2nd order differential operator whose principal symbol is $\sigma_L(\Delta_M)(x, \xi) = ||\xi||^2$. We

Received by the editors April 15, 2002 and, in revised form, October 10, 2002.
2000 Mathematics Subject Classification. Primary 58J52, 58J50.
Key words and phrases. Zeta-determinant, gluing formula, Laplacian, Dirichlet (Neumann)
boundary condition, absolute (relative) boundary condition, adiabatic decomposition.
The author was partially supported by Korea Research Foundation Grant KRF-2000-015-
DP0045.

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assumed that $\Delta_M$ is $-\partial_u^2 + \Delta_Y$ on $N$, where $\partial_u$ is the unit normal vector field to $Y$ on $N$, outward to $M_1$, and $\Delta_Y$ is a Laplacian on $Y$.

We denote by $D$, $B$ the Dirichlet boundary conditions on $Z$, $Y$ and by $C$ the Neumann boundary condition on $Y$, defined as follows:

$$D : C^\infty(M_1) \to C^\infty(Z \cap M_1) \quad \text{by} \quad D(\phi) = \phi|_Z,$$

$$B : C^\infty(M_1) \to C^\infty(Y) \quad \text{by} \quad B(\phi) = \phi|_Y,$$

$$C : C^\infty(M_1) \to C^\infty(Y) \quad \text{by} \quad C(\phi) = (\partial_u \phi)|_Y.$$

Then the Laplacian $\Delta_{M,D}$ ($\Delta_{M,B,D}$, $\Delta_{M,C,D}$) with the Dirichlet condition on $Z$ (the Dirichlet condition on $Y$ and $Z$, the Neumann condition on $Y$ and the Dirichlet condition on $Z$) is defined by the same operator $\Delta_M$ ($\Delta_{M,D}$) with domains as follows:

$$\text{Dom}(\Delta_{M,D}) = \{ \phi \in C^\infty(M) \mid D(\phi) = 0 \},$$

$$\text{Dom}(\Delta_{M,B,D}) = \{ \phi \in C^\infty(M_1) \mid B(\phi) = 0, D(\phi) = 0 \},$$

$$\text{Dom}(\Delta_{M,C,D}) = \{ \phi \in C^\infty(M_1) \mid C(\phi) = 0, D(\phi) = 0 \}.$$

For computational reasons, we consider $\Delta_{M,D}^m + t^m$, $\Delta_{M,B,D}^m + t^m$ and $\Delta_{M,C,D}^m + t^m$ ($t \in \mathbb{R}^+$) rather than $\Delta_{M,D}$, $\Delta_{M,B,D}$ and $\Delta_{M,C,D}$, where $D_m$, $B_m$ and $C_m$ are the Dirichlet and the Neumann boundary conditions corresponding to $\Delta_{M,D}^m$, $\Delta_{M,B}^m$, (or $\Delta_{M,D}^m$, $\Delta_{M,B}^m$, $\Delta_{M,C}^m + t^m$) defined as follows:

$$D_m = (D, D\Delta_M, \ldots, D\Delta_M^{m-1}),$$

$$B_m = (B, B\Delta_M, \ldots, B\Delta_M^{m-1}),$$

$$C_m = (C, C\Delta_M, \ldots, C\Delta_M^{m-1}).$$

Note that

$$\Delta_{M,D}^m + t^m = \left\{ \prod_{k=-\frac{m}{2}}^{\frac{m-1}{2}} (\Delta_{M,D} + e^{\frac{ik\pi}{m}} t) \right\} \text{if } m \text{ is odd},$$

$$\Delta_{M,D}^m + t^m = \left\{ \prod_{k=-\frac{m}{2}}^{\frac{m-1}{2}} (\Delta_{M,D} + e^{\frac{ik\pi}{m}} t) \right\} \text{if } m \text{ is even}.$$

For $-\left[ \frac{m}{2} \right] \leq k \leq \left[ \frac{m-1}{2} \right]$, let $\alpha_k = e^{\frac{2ik\pi}{m}}$ if $m$ is odd, and $\alpha_k = e^{\frac{2i(k+\frac{1}{2})\pi}{m}}$ if $m$ is even.

Now we describe the so-called Dirichlet-to-Neumann operator $R(\alpha_k) : C^\infty(Y) \to C^\infty(Y)$ associated to $\Delta_{M,D} + \alpha_1 t$ on $Y$. Let $P_1(\alpha_k t) : C^\infty(Y) \to C^\infty(M_1)$ be the Poisson operator on $Y$ associated to $\Delta_{M,D} + \alpha_k t$, which is characterized by the following equations (for details see [3], [1], [2]):

$$BP_1(\alpha_k t) = I_{0,Y}, \quad DP_1(\alpha_k t) = 0, \quad (\Delta_M + \alpha_k t)P_1(\alpha_k t) = 0.$$

Then $R(\alpha_k)$ is defined by the composition of the following maps:

$$C^\infty(Y) \xrightarrow{\delta_{M,D}} C^\infty(Y) \oplus C^\infty(Y) \xrightarrow{(P_1(\alpha_k), P_2(\alpha_k))} C^\infty(M_1) \oplus C^\infty(M_2) \xrightarrow{(C_1, C_2)} C^\infty(Y) \oplus C^\infty(Y) \xrightarrow{\delta_i} C^\infty(Y),$$

where $\delta_{M,D}(g) = (g, g), \ C_1(\phi_1) = (\partial_u \phi_1)|_Y, \ C_2(\phi_2) = (\partial_u \phi_2)|_Y$ and $\delta_i(g, h) = g - h$.

It is known that $R(\alpha_k)$ is a $\Psi$DO of order 1 (cf. Theorem 2.1) and by choosing $\pi$ as an Agmon angle, $\log \text{Det} R(\alpha_k)$ is well defined. The following theorem is due to Burghelea, Friedlander and Kappeler ([8], see also [3] and [1]).
Theorem 1.1.

\[
\log \text{Det}(\Delta_{M,D}^m + t^m) - \log \text{Det}(\Delta_{M_1,B,D}^m + t^m) - \log \text{Det}(\Delta_{M_2,B,D}^m + t^m)
\]

\[
= - \sum_{k=-[\frac{m}{2}]}^{[\frac{m}{2}-1]} c_k + \sum_{k=-[\frac{m}{2}]}^{[\frac{m}{2}-1]} \log \text{Det}R(\alpha_k t),
\]

where \( c_k \) is the zero coefficient in the asymptotic expansion of \( \log \text{Det}R(\alpha_k t) \) as \( t \to \infty \).

Remark. In [3] and [8], Theorem 1.1 was proved only in the case \( Z = \emptyset \). However, the proof can be extended without any modification to the case that \( Z \) is non-empty.

The purpose of this paper is to compute the zero coefficients in Theorem 1.1 under the assumption of the product structures on \( N \) and \( E|_N \), and then to apply this result to prove the adiabatic decomposition theorems for the zeta-determinant of a Laplacian and the analytic torsion. We first have the following theorem.

Theorem 1.2. We assume the product structures of \( M \) and \( E \) on \( N \) and \( \Delta_M = -\partial^*_M + \Delta_Y \) on \( N \). Then \( \sum_k c_k = m \log 2 \cdot \left( \zeta_{\Delta_Y}(0) + \dim \text{Ker} \Delta_Y \right) \).

Setting \( t = 0 \), we get the following corollary.

Corollary 1.3. We further assume that \( \Delta_{M,D} \) is invertible. Then

\[
\log \text{Det} \Delta_{M,D}^m - \log \text{Det} \Delta_{M_1,B,D}^m - \log \text{Det} \Delta_{M_2,B,D}^m
\]

\[
- \log 2 \cdot \left( \zeta_{\Delta_Y}(0) + \dim \text{Ker} \Delta_Y \right) + \log \text{Det}R.
\]

Remarks. (1) If \( \dim Y \) is odd, it is well-known that \( \zeta_{\Delta_Y}(0) + \dim \text{Ker} \Delta_Y = 0 \). In this case, the assertion in Corollary 1.3 can be written as follows:

\[
\log \text{Det} \Delta_{M,D}^m - \log \text{Det} \Delta_{M_1,B,D}^m - \log \text{Det} \Delta_{M_2,B,D}^m = \log \text{Det}R,
\]

which was observed in [7].

(2) Theorem 1.1, Theorem 1.2 and Corollary 1.3 also hold when we impose the absolute (or the relative) boundary condition on \( Z \) (see Theorem 5.2).
If \( f \in C^\infty(Y) \), choose \( \phi_1 \in C^\infty(M_1) \) satisfying \( \Delta_{M_1} \phi_1 = 0 \), \( \phi_1|_Z = 0 \) and \( \phi_1|_Y = f \). We define

\[
Q_1(f) = (\partial_u \phi_1)|_Y, \quad Q_2(f) = (-\partial_u \phi_2)|_Y.
\]

Then each \( Q_i \) is an elliptic \( \Psi DO \) of order 1 (cf. Theorem 2.1), and the Dirichlet-to-Neumann operator \( R \) is \( R = Q_1 + Q_2 \). The following is the second result of this paper.

**Theorem 1.4.** We assume that both \( Q_1 + \sqrt{\Delta_Y} \) and \( Q_2 + \sqrt{\Delta_Y} \) are invertible operators and \( k = \dim \ker \Delta_Y \). We further assume that \( \Delta_{M,D} \) is invertible for \( r \) large enough. Then

\[
\lim_{r \to \infty} \left\{ \log \det(\Delta_{M,D}) - \log \det(\Delta_{M_1,r,B,D}) - \log \det(\Delta_{M_2,r,B,D}) + k \log r \right\} = \frac{1}{2} \log \det \Delta_Y.
\]

**Remarks.** (1) If \( \Delta_Y \) has non-trivial kernel, we define \( \det \Delta_Y \) from the zeta function \( \zeta_{\Delta_Y}(s) \) consisting of only non-zero eigenvalues.

(2) If \( \Delta_M \) is a connection Laplacian for a connection compatible with the inner product, each \( Q_i \) is a non-negative operator (Lemma 4.3).

(3) Suppose that \( \Delta_M = A^2 \) for a Dirac operator \( A \) which has the form \( G(\partial_u + B) \) near \( Y \) with \( G \) a bundle automorphism satisfying

\[
G^* = -G, \quad G^2 = -Id, \quad B^* = B, \quad GB = -BG.
\]

Here \( G \) and \( B \) do not depend on the normal coordinate \( u \). Then the invertibility of both \( Q_1 + \sqrt{B} \) and \( Q_2 + \sqrt{B} \) is equivalent to the non-existence of the extended \( L^2 \)-solutions of \( A_{M_1,\infty} \), \( A_{M_2,\infty} \) on \( M_{1,\infty} \) and \( M_{2,\infty} \) (Corollary 4.5).

(4) Suppose that \( \Delta_M \) is a connection Laplacian or a Dirac Laplacian for a connection compatible with the inner product, and \( \Delta_{M,D} \) is invertible. Then the invertibility of both \( Q_1 + \sqrt{\Delta_Y} \) and \( Q_2 + \sqrt{\Delta_Y} \) implies the invertibility of \( \Delta_{M_1,D} \) for \( r \) large enough (Lemma 4.6).

Let \( M_1,r \) be the double of \( M_{1,r} \). Then it is a well-known fact that

\[
\log \det(\Delta_{M_1,r,D,D}) = \log \det(\Delta_{M_1,r,C,D}) + \log \det(\Delta_{M_1,r,B,D}).
\]

Combining this fact with Corollary 1.3 and Theorem 1.4, we have the following result.

**Corollary 1.5.** We assume the hypotheses in Theorem 1.4. Then:

1. \[
\lim_{r \to \infty} \left\{ \log \det(\Delta_{M_1,r,C,D}) - \log \det(\Delta_{M_1,r,B,D}) + k \log r \right\} = \frac{1}{2} \log \det(\Delta_Y).
\]
2. \[
\lim_{r \to \infty} \left\{ \log \det(\Delta_{M_1,D}) - \log \det(\Delta_{M_1,r,C,D}) - \log \det(\Delta_{M_2,r,B,D}) \right\} = 0.
\]

Finally we discuss the adiabatic decomposition of the analytic torsion into the analytic torsions with the absolute and relative boundary conditions.

Here we assume that \( M \) is a closed manifold with a hypersurface \( Y \) and \( M \) has a product structure near \( Y \). We define \( M_r \), \( M_{1,r} \) and \( M_{2,r} \) as above so that \( M_r = M_{1,r} \cup (0) \times Y \cup M_{2,r} \). Suppose that \( \rho_M, (\rho_{M_1,r}, \rho_{M_2,r}, \rho_Y) \) is an orthogonal representation of \( \pi_1(M_r), \pi_1(M_{1,r}), \pi_1(M_{2,r}), \pi_1(Y) \) to \( SO(n) \), respectively. Then we can define the analytic torsions \( \tau(M_r, \rho_M), \tau_{abs}(M_{1,r}, \rho_{M_{1,r}}), \tau_{rel}(M_{1,r}, \rho_{M_{1,r}}) \) \((i = 1, 2)\), \( \tau(Y, \rho_Y) \) in the standard way (for the definitions, see Section 5). Our
goal is to recover the Klimek-Wojciechowski result about the analytic torsion in \cite{[6]} as follows.

First, let us consider $M_{1,r}$ (a manifold with boundary $Y$) only. For a given representation $\rho_{M_{1,r}} : \pi_1(M_{1,r}) \to SO(n)$ and the natural homomorphism $\iota_Y : \pi_1(Y) \to \pi_1(M_{1,r})$, define $\rho_Y : \pi_1(Y) \to SO(n)$ by $\rho_Y = \rho_{M_{1,r}} \circ \iota_Y$. We denote by $\Delta_Y^q = (\Delta^q_{M_{1,r}})$ the Hodge Laplacian acting on $q$-forms on $Y$ (on $M_{1,r}$) and valued in $E_{\rho_Y}(E_{\rho_{M_{1,r}}})$, where $E_{\rho_Y} = \tilde{Y} \times_{\rho_Y} \mathbb{R}^n$ with $\tilde{Y}$ the universal covering space of $Y$ ($E_{\rho_{M_{1,r}}}$ is defined in the same way). We define $Q_1^q$ the same way as in Theorem 1.4 with the bundle $E = \bigwedge^q T^* M_{1,r} \otimes E_{\rho_{M_{1,r}}}$, if necessary, by tensoring $\mathbb{C}$ on $E$, we regard $E$ as a complex vector bundle. Then we have the following theorem.

**Theorem 1.6.** Suppose that for each $q$, $Q_1^q + \begin{pmatrix} \sqrt{\Delta_Y^q} & 0 \\ 0 & \sqrt{\Delta_Y^q} \end{pmatrix}$ is an invertible operator on $\{-r\} \times Y$ and $H^q(M_{1,r}; \rho_{M_{1,r}})$, $H^q(M_{1,r}; Y; \rho_{M_{1,r}})$ are trivial groups. Then

$$\lim_{r \to -\infty} \{ \log \tau_{abs}(M_{1,r}; \rho_{M_{1,r}}) - \log \tau_{rel}(M_{1,r}; \rho_{M_{1,r}}) \} = \log \tau(Y; \rho_Y).$$

**Remark.** If $Q_1^q + \begin{pmatrix} \sqrt{\Delta_Y^q} & 0 \\ 0 & \sqrt{\Delta_Y^q} \end{pmatrix}$ is invertible, by Corollary 4.5 there are no extended $L^2$-solutions of $d_q + d_q^*$ on $M_{1,\infty}$, which implies that $\text{Ker} \Delta_{\text{rel}}^{-1} = \text{Ker} \Delta_Y^q = 0$ (cf. \cite{[1], [2], [5]}).

Next, we consider the closed manifold $M_r$ and manifolds with boundary $M_{i,r}$ ($i = 1, 2$). For a given representation $\rho_{M_r} : \pi_1(M_r) \to SO(n)$ and the natural homomorphisms $\iota_{M_{i,r}} : \pi_1(M_{i,r}) \to \pi_1(M_r)$, $\iota_Y : \pi_1(Y) \to \pi_1(M_{i,r})$, define $\rho_{M_{i,r}} : \pi_1(M_{i,r}) \to SO(n)$, $\rho_Y : \pi_1(Y) \to SO(n)$ by $\rho_{M_{i,r}} = \rho_{M_r} \circ \iota_{M_{i,r}}$, $\rho_Y = \rho_{M_{i,r}} \circ \iota_Y$. We also define $\Delta_Y^q$, $Q_1^q$ and $Q_2^q$ as in Theorem 1.6.

**Theorem 1.7.** Suppose that, for each $q$,

$$Q_1^q + \begin{pmatrix} \sqrt{\Delta_Y^q} & 0 \\ 0 & \sqrt{\Delta_Y^q} \end{pmatrix} \quad \text{and} \quad Q_2^q + \begin{pmatrix} \sqrt{\Delta_Y^q} & 0 \\ 0 & \sqrt{\Delta_Y^q} \end{pmatrix}$$

are invertible operators on $\{-r\} \times Y$, $\{r\} \times Y$, and $H^q(M; \rho_{M_r})$, $H^q(M_{1,r}; Y; \rho_{M_{1,r}})$, $H^q(M_{2,r}; Y; \rho_{M_{1,r}})$ are trivial groups. Then:

1. $$\lim_{r \to -\infty} \left( \log \text{Det} \Delta_{M_r}^q - \log \text{Det} \Delta_{M_{1,r}, \text{abs}}^q - \log \text{Det} \Delta_{M_{2,r}, \text{rel}}^q \right) = 0.$$

2. $$\lim_{r \to -\infty} \left( \log \tau(M; \rho_{M_r}) - \log \tau_{abs}(M_{1,r}; \rho_{M_{1,r}}) - \log \tau_{rel}(M_{2,r}; \rho_{M_{2,r}}) \right) = 0.$$

**Remark.** Recently J. Park and K. Wojciechowski proved the following result in \cite{[10]}. Suppose that $M$ is an odd-dimensional compact manifold with $M = M_1 \cup Y \ M_2$ and $D$ is a Dirac operator acting on smooth sections of a Clifford module bundle $E$ with $D = G(\partial_0 + B)$ near $Y$. Denote by $P_+$, $P_-$ the Atiyah-Patodi-Singer boundary conditions projecting the positive and negative eigenspaces of $B$, respectively. Assume that

$$\text{Ker} B = \{0\}, \quad \text{Ker} L_2 D_{1,\infty} = \text{Ker} L_2 D_{2,\infty} = \{0\},$$

where $\text{Ker} L_2 D_{i,\infty}$ is the set of all extended $L^2$-solutions of $D_{i,\infty}$ on $M_{i,\infty}$. Then

$$\lim_{r \to -\infty} \left\{ \log \text{Det} D_r^2 - \log \text{Det} D_{M_{1,r}, P_+}^2 - \log \text{Det} D_{M_{2,r}, P_-}^2 \right\} = -2 \cdot \zeta_{B^2}(0).$$
2. Asymptotic symbol of $R(\alpha_k t)$

In this section, we are going to describe the asymptotic symbol of $R(\alpha_k t)$. The following method was observed by I.M. Gelfand.

We start by defining $Q_i(\alpha_k t) : C^\infty(Y) \to C^\infty(Y)$ $(i = 1, 2)$ as follows. For $f \in C^\infty(Y)$, choose $\phi_i \in C^\infty(M_i)$ such that

$$\left(\Delta_{M_i} + \alpha_k t\right) \phi_i = 0, \quad \phi_i|_Y = f, \quad \phi_i|_Z = 0.$$

Then we define

$$Q_1(\alpha_k t)(f) = (\partial_u \phi_1)|_Y \quad \text{and} \quad Q_2(\alpha_k t)(f) = (-\partial_u \phi_1)|_Y.$$ 

From this definition, we get

$$R(\alpha_k t) = Q_1(\alpha_k t) + Q_2(\alpha_k t),$$

and it’s enough to consider $Q_1(\alpha_k t)$ only. From now on we denote $Q_1(\alpha_k t)$ simply by $Q(\alpha_k t)$.

For $f \in C^\infty(Y)$, let $\varphi$ be a solution of $\Delta_{M_1} + \alpha_k t$ with $\varphi|_Y = f$ and $\varphi|_Z = 0$. Then

$$\frac{d}{du} \varphi(u, y) = Q_u(\alpha_k t) \varphi(u, y),$$

where $Q_u(\alpha_k t)$ is defined similarly to $Q(\alpha_k t) = Q_0(\alpha_k t)$ at the level $\{u\} \times Y$:

$$\frac{d^2}{du^2} \varphi(u, y) = \left(\frac{d}{du} Q_u(\alpha_k t)\right) \varphi(u, y) + Q_u(\alpha_k t)^2 \varphi(u, y).$$

For $0 \leq u < 1$,

$$(\Delta_Y + \alpha_k t) \varphi(u, y) = \left(\frac{d}{du} Q_u(\alpha_k t)\right) \varphi(u, y) + Q_u(\alpha_k t)^2 \varphi(u, y).$$

Consequently, for $0 \leq u < 1$,

$$\frac{d}{du} Q_u(\alpha_k t) = -Q_u(\alpha_k t)^2 + (\Delta_Y + \alpha_k t).$$

Now let us consider the asymptotic symbol of $Q_u(\alpha_k t)$ as follows:

$$\sigma(Q_u(\alpha_k t)) \sim q_1(u, y, \xi) + q_0(u, y, \xi) + \cdots + q_{1-j}(u, y, \xi) + \cdots,$$

where $q_{1-j}(u, y, \xi)$ is the homogeneous part of $\sigma(Q_u(\alpha_k t))$ of order $1-j$ with respect to $\xi$. Then

$$\sigma \left(\frac{d}{du} Q_u(\alpha_k t)\right) \sim \frac{d}{du} q_1(u, y, \xi) + \frac{d}{du} q_0(u, y, \xi) + \cdots + \frac{d}{du} q_{1-j}(u, y, \xi) + \cdots.$$

Note that

$$\sigma(Q_u(\alpha_k t)^2) \sim \sum_{k=0}^{\infty} \sum_{|\omega|+i+j=k, i,j \geq 0} \frac{1}{\omega!} d_\xi^\omega \ q_{1-i}(u, y, \xi) \cdot D_y^\omega q_{1-j}(u, y, \xi)$$

$$= q_1^2(u, y, \xi) + (d_\xi q_1 D_y q_1 + q_0 q_1 + q_1 q_0) + \cdots.$$

Suppose that

$$\sigma(\Delta_Y + \alpha_k t) = (p_2(y, \xi) + \alpha_k t I d) + p_1(y, \xi) + p_0(y, \xi).$$
Since \( \frac{d}{dt} Q_u(\alpha_k t) \) is a \( \Psi \)DO of order 1, \( q_1^2(u, y, \xi) = p_2(y, \xi) + \alpha_k t I_d \). Applying the argument of Lemma 3.3 in \cite{8} to the double of a manifold with boundary, one can show that
\[
(2.5) \quad q_1(u, y, \xi) = \sqrt{p_2(y, \xi) + \alpha_k t I_d}.
\]
Hence \( q_1 \) does not depend on \( u \), and \( \frac{d}{du} q_1(u, y, \xi) = 0 \). Again, from (2.2), (2.3) and (2.4), since \( q_1 \) is a scalar matrix, \( (d_\xi q_1 D_y q_1 + 2q_1 q_0) = p_1(y, \xi) \) and
\[
q_0(u, y, \xi) = (2q_1(y, \xi))^{-1} (p_1(y, \xi) - d_\xi q_1(y, \xi) \cdot D_y q_1(y, \xi)).
\]
Hence \( q_0(u, y, \xi) \) does not depend on \( u \), and \( \frac{d}{du} q_0(u, y, \xi) = 0 \). In general,
\[
q_{-1} = (2q_1)^{-1} \left\{ - \sum_{|\omega|+|i+j|=2} \frac{1}{\omega!} d_\xi^\omega q_{1-i}(y, \xi) \cdot D_y^\omega q_{1-j}(y, \xi) + p_0(y, \xi) \right\}
\]
and for \( k \geq 3 \),
\[
q_{-k} = (2q_1)^{-1} \left\{ - \sum_{|\omega|+|i+j|=k} \frac{1}{\omega!} d_\xi^\omega q_{1-i}(y, \xi) \cdot D_y^\omega q_{1-j}(y, \xi) \right\}.
\]
Hence, each \( q_{-k} \) does not depend on \( u \), and this implies that \( \frac{d}{du} Q_u(\alpha_k t) \) is a smoothing operator. Setting \( u = 0 \) in (2.2), we see that
\[
(2.6) \quad Q(\alpha_k t)^2 = (\Delta_Y + \alpha_k t) + \text{ a smoothing operator},
\]
and we get the following theorem.

**Theorem 2.1.** Under the assumption of the product structure near \( N \), we have the following:

1. \( Q(\alpha_k t) = \sqrt{\Delta_Y + \alpha_k t} + \text{ a smoothing operator} \).
2. \( R(\alpha_k t) = 2\sqrt{\Delta_Y + \alpha_k t} + \text{ a smoothing operator} \).

**Proof.** It’s enough to show the first statement. From (2.5) we have
\[
Q(\alpha_k t) = \sqrt{\Delta_Y + \alpha_k t} + A,
\]
where \( A \) is an operator of order 0. Squaring both sides and using (2.6), we have
\[
Q(\alpha_k t)^2 = (\Delta_Y + \alpha_k t) + \sqrt{\Delta_Y + \alpha_k t} A + A \sqrt{\Delta_Y + \alpha_k t} + A^2
\]
\[
= (\Delta_Y + \alpha_k t) + \text{ a smoothing operator}.
\]
Hence \( \sqrt{\Delta_Y + \alpha_k t} A + A \sqrt{\Delta_Y + \alpha_k t} + A^2 \) is a smoothing operator, which implies that \( A \) is a smoothing operator. \( \square \)

3. **Computation of the zero coefficient of \( \log \text{Det} R(\alpha_k t) \) as \( t \to \infty \)**

It is shown in \cite{8} that \( \log \text{Det} R(\alpha_k t) \) has an asymptotic expansion as \( t \to \infty \) and each coefficient can be computed by the asymptotic symbol of \( R(\alpha_k t) \). Hence, from Theorem 2.1, \( \log \text{Det} R(\alpha_k t) \) and \( \log \text{Det} (2\sqrt{\Delta_Y + \alpha_k t}) \) have the same asymptotic expansions as \( t \to \infty \). In this section, we are going to compute the asymptotic expansion of \( \log \text{Det} (2\sqrt{\Delta_Y + \alpha_k t}) \) by using the method in \cite{12}.

Note that
\[
(3.1) \quad \log \text{Det} (2\sqrt{\Delta_Y + \alpha_k t}) = \log 2 \cdot \zeta(\Delta_Y + \alpha_k t)(0) + \frac{1}{2} \log \text{Det} (\Delta_Y + \alpha_k t),
\]

and we are going to consider \( \log \text{Det}(\Delta_Y + \alpha_k t) \). Since \( \text{Re}(\alpha_k) \) is possibly negative, we avoid this difficulty as follows. Put \( \alpha_k = e^{i\theta_k} \) with \( \theta_k = \frac{2k\pi}{m} \) for \( m \) odd and \( \frac{(2k+1)\pi}{m} \) for \( m \) even. Choose an angle \( \phi_k \) with \( 0 \leq |\phi_k| < \frac{\pi}{2} \) so that \( \text{Re}(e^{i(\theta_k - \phi_k)}) > 0 \). (In fact, if \( 0 \leq |\theta_k| < \frac{\pi}{2} \), we choose \( \phi_k = 0 \).) Then

\[
\log \text{Det}(\Delta_Y + \alpha_k t) = \log \text{Det}\{e^{i\phi_k}(e^{-i\phi_k}\Delta_Y + e^{i(\theta_k - \phi_k)})t\}
\]

(3.2)

Put \( \tilde{\theta}_k = \theta_k - \phi_k \). Then

\[
\zeta_{e^{-i\phi_k}\Delta_Y + e^{i(\theta_k - \phi_k)}}(s) = \frac{1}{\Gamma(s)} \int_0^\infty r^{s-1} \text{Tr} e^{-r(e^{-i\phi_k}\Delta_Y + e^{i(\theta_k - \phi_k)})} dr
\]

The following lemma is a well-known fact.

**Lemma 3.1.** As \( r \to 0 \), we have the following asymptotic expansion:

\[
\text{Tr} e^{-r(e^{-i\phi_k}\Delta_Y + e^{i(\theta_k - \phi_k)})} \sim b_1 r^{-\frac{m-1}{2}} + b_2 r^{-\frac{m-3}{2}} + \cdots + b_m + b_{m-1} r^\frac{1}{2} + \cdots
\]

with \( b_m = \zeta_{\Delta_Y}(0) + \text{dim Ker} \Delta_Y \).

Now we are going to compute the asymptotic expansion of \( \zeta_{e^{-i\phi_k}\Delta_Y + e^{i(\theta_k - \phi_k)}}(s) \) as \( t \to \infty \):

\[
\zeta_{e^{-i\phi_k}\Delta_Y + e^{i(\theta_k - \phi_k)}}(s) = \frac{1}{\Gamma(s)} \int_0^\infty r^{s-1} e^{-r e^{i\phi_k}} \text{Tr} e^{-r e^{-i\phi_k}\Delta_Y} dr
\]

As \( t \to \infty \),

\[
\zeta_{e^{-i\phi_k}\Delta_Y + e^{i(\theta_k - \phi_k)}}(s) \sim t^{-s} \sum_{j=1}^\infty \frac{1}{\Gamma(s)} b_j \int_0^\infty u^{s-1} \left( \frac{u}{t} \right)^{\frac{m-j}{2}} e^{-ue^{i\phi_k}} du
\]

Consider the contour integral \( \int_C e^{s+\frac{m-1}{2}}e^{-z}dz \) for \( \text{Res} > \frac{m-1}{2} \), where

\[
C = \{ r e^{i\theta_k} \mid 0 \leq r \leq R \} \cup \{ e^{i\theta_k} \mid 0 \leq \theta \leq \tilde{\theta}_k \}
\]

and oriented counterclockwise. Then one can check that

\[
\int_0^\infty (ue^{i\phi_k})^{s+\frac{m-1}{2}}e^{-ue^{i\phi_k}}(e^{i\phi_k}) du = \int_0^\infty r^{s+\frac{m-1}{2}}e^{-r} dr = \Gamma(s + \frac{j - m}{2}).
\]
We therefore obtain the following asymptotic expansion for $t \to \infty$:

$$
\zeta(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(s) \sim \sum_{j=1}^{\infty} b_j (e^{-i\theta_k})^s + \frac{i^{-\frac{m}{2}}}{\Gamma(s)} \frac{\Gamma(s + \frac{j-m}{2})}{\Gamma(s+1)} t^{-s+\frac{m-j}{2}}
$$

$$
= s \sum_{j \neq m}^{\infty} b_j (e^{-i\theta_k})^s + \frac{i^{-\frac{m}{2}}}{\Gamma(s)} \frac{\Gamma(s + \frac{j-m}{2})}{\Gamma(s+1)} t^{-s+\frac{m-j}{2}} + b_m e^{-i\theta_k} s t^{-s}.
$$

This gives the asymptotic expansion of $\zeta(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(s)$ as $t \to \infty$. In view of Theorem 1.1 we are mainly interested in the zero coefficients in the asymptotic expansions of $\zeta(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(0)$ and $\zeta'(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(0)$ as $t \to \infty$.

First, setting $s = 0$, the zero coefficient $\pi_0(\zeta(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(0))$ in the asymptotic expansion of $\zeta(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(0)$ is the following:

$$
(3.3) \quad \pi_0(\zeta(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(0)) = b_m = \zeta\Delta_Y(0) + \text{dimKer} \Delta_Y.
$$

Taking the derivative at $s = 0$, the zero coefficient of $\zeta'(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(0)$ can be obtained only in the term $b_m e^{-i\theta_k} s t^{-s}$. Hence, by (3.2) and (3.3), the zero coefficient $\pi_0(\Delta_Y + \alpha_k t)$ in the asymptotic expansion of $\log \text{Det}(\Delta_Y + \alpha_k t)$ as $t \to \infty$ is

$$
(3.4) \quad \pi_0(\Delta_Y + \alpha_k t) = i\theta_k (\zeta\Delta_Y(0) + \text{dimKer} \Delta_Y) + i(\theta_k - \phi_k)(\zeta\Delta_Y(0) + \text{dimKer} \Delta_Y)
$$

We summarize the above computations as follows.

**Proposition 3.2.** The zero coefficients in the asymptotic expansions of $\zeta(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(0)$ and $\log \text{Det}(\Delta_Y + \alpha_k t)$ as $t \to \infty$ are the following:

1. $\pi_0(\zeta(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(0)) = \zeta\Delta_Y(0) + \text{dimKer} \Delta_Y$.
2. $\pi_0(\Delta_Y + \alpha_k t) = i\theta_k (\zeta\Delta_Y(0) + \text{dimKer} \Delta_Y)$, where $\alpha_k = e^{i\theta_k}$.

Now we are ready to compute $c = \sum_k c_k$ in Theorem 1.1. Since $\zeta(\Delta_Y + \alpha_k t)(0) = \zeta(e^{-i\theta_k} \Delta_Y + e^{i\theta_k} t)(0)$, from (3.1) and Proposition 3.2 we get

$$
c_k = \log 2 \cdot (\zeta\Delta_Y(0) + \text{dimKer} \Delta_Y) + \frac{1}{2} i\theta_k (\zeta\Delta_Y(0) + \text{dimKer} \Delta_Y),
$$

and hence

$$
\sum_k c_k = m \log 2 \cdot (\zeta\Delta_Y(0) + \text{dimKer} \Delta_Y).
$$

This completes the proof of Theorem 1.2.

### 4. The Adiabatic Decomposition of the Zeta-Determinant of a Laplacian

In this section we are going to prove Theorem 1.4. Recall that

$$
M_{1,r} = M_1 \cup_{Y} [-r, 0] \times Y, \quad M_{2,r} = M_2 \cup_{Y} [0, r] \times Y,
$$

where we identify $Y$ with $\{-r\} \times Y$ and $Y$ with $\{r\} \times Y$. Then

$$
(4.1) \quad M_r = M_{1,r} \cup_{\{0\} \times Y} M_{2,r}.
$$

Throughout this section we denote $\{r\} \times Y$ by $Y_r$, the Dirichlet (Neumann) condition on $Y_r$ by $B_r$ ($C_r$) and the Dirichlet condition on $Z$ by $D$. We assume that $\Delta_{M,D}$
is invertible. Then, under certain conditions, $\Delta_{M_r,D}$ is also invertible for $r$ large enough (Lemma 4.6).

From the decomposition (4.1) and Corollary 1.3, we have

$$\log \text{Det} \Delta_{M_r,D} = \log \text{Det} \Delta_{M_{1,r},B_0,D} + \log \text{Det} \Delta_{M_{2,r},B_0,D}$$

$$- \log 2 \cdot (\xi_Y(0) + \text{dim Ker} \Delta_Y) + \log \text{Det} R_{M_r}.$$  \hspace{1cm} (4.2)

From the decomposition $M_r = (M_1 \cup M_2) \cup N_r$ with $N_r = [-r,r] \times Y$, we have

$$\log \text{Det} \Delta_{M_r,D} = \log \text{Det} \Delta_{(M_1 \cup M_2),B_r,D} + \log \text{Det} \Delta_{N_r,B_r,B_r}$$

$$- \log 2 \cdot (\xi_Y(0) + \text{dim Ker} \Delta_Y) + \log \text{Det} R_{-r,r}$$

$$= \log \text{Det} \Delta_{M_1,B_r,D} + \log \text{Det} \Delta_{M_2,B_r,D} + \log \text{Det} \Delta_{N_r,B_r,B_r}$$

$$- \log 2 \cdot (\xi_Y(0) + \text{dim Ker} \Delta_Y) + \log \text{Det} R_{r,r}.$$  \hspace{1cm} (4.3)

where $R_{-r,r} : C^\infty(Y_{-r}) \oplus C^\infty(Y_r) \to C^\infty(Y_{-r}) \oplus C^\infty(Y_r)$ is the Dirichlet-to-Neumann operator corresponding to the decomposition $(M_1 \cup M_2) \cup N_r$.

Put $N_{-r,0} = [-r,0] \times Y$ and $N_{0,r} = [0,r] \times Y$. Since $M_{1,r} = M_1 \cup N_{-r,0}$ and $M_{2,r} = M_2 \cup N_{0,r}$, we have

$$\log \text{Det} \Delta_{M_{1,r},B_0,D} = \log \text{Det} \Delta_{M_1,B_r,D} + \log \text{Det} \Delta_{N_{-r,0},B_{-r},B_0}$$

$$- \log 2 \cdot (\xi_Y(0) + \text{dim Ker} \Delta_Y) + \log \text{Det} R_{M_{1,r}}.$$  \hspace{1cm} (4.4)

$$\log \text{Det} \Delta_{M_{2,r},B_0,D} = \log \text{Det} \Delta_{M_2,B_r,D} + \log \text{Det} \Delta_{N_{0,r},B_{-r},B_0}$$

$$- \log 2 \cdot (\xi_Y(0) + \text{dim Ker} \Delta_Y) + \log \text{Det} R_{M_{2,r}}.$$  \hspace{1cm} (4.5)

Here $\Delta_{N_{-r,0},B_{-r},B_0} = -\partial^2_u + \Delta_Y$ with the domain $\{ \phi \in C^\infty(N_{-r,0}) \mid \phi|_{Y_{-r}} = \phi|_{Y_0} = 0 \}$ and $R_{M_{1,r}}$ is the Dirichlet-to-Neumann operator corresponding to the decomposition $M_{1,r} = M_1 \cup ([-r,0] \times Y)$. $\Delta_{N_{0,r},B_{-r},B_0}$ and $R_{M_{2,r}}$ are defined similarly.

Then from (4.2)–(4.5), we have

$$- \log 2 \cdot (\xi_Y(0) + \text{dim Ker} \Delta_Y) + \log \text{Det} R_{M_r}$$

$$= \log \text{Det} \Delta_{N_r,B_r,B_r} - \log \text{Det} \Delta_{N_{-r,0},B_{-r},B_0} - \log \text{Det} \Delta_{N_{0,r},B_{-r},B_0}$$

$$+ \log \text{Det} R_{-r,r} - \log \text{Det} R_{M_{1,r}} - \log \text{Det} R_{M_{2,r}}.$$  \hspace{1cm} (4.6)

From the decomposition of $N_r$ as

$$N_r = ([-r,0] \times Y) \cup ([0,r] \times Y),$$

we have

$$\log \text{Det} \Delta_{N_r,B_r,B_r} - \log \text{Det} \Delta_{N_{-r,0},B_{-r},B_0} - \log \text{Det} \Delta_{N_{0,r},B_{-r},B_0}$$

$$= - \log 2 \cdot (\xi_Y(0) + \text{dim Ker} \Delta_Y) + \log \text{Det} R_{N_r},$$  \hspace{1cm} (4.7)

where $R_{N} : C^\infty(Y_0) \to C^\infty(Y_0)$ is defined as follows. For $f \in C^\infty(Y_0)$, choose $\phi(u,y)$ so that $(-\partial^2_u + \Delta_Y)\phi = 0$ on $N_r - Y_0$, $\phi|_{Y_0} = f$, $\phi|_{Y_{-r}} = \phi|_{Y_r} = 0$. Then, $R_{N}(f) = (\partial_u(\phi|_{N_{-r,0}}) - \partial_u(\phi|_{N_{0,r}}))|_{Y_0}$. Hence, we obtain from (4.6) and (4.7)

$$\log \text{Det} R_{M_r} = \log \text{Det} R_{N_r} + \log \text{Det} R_{r,r} - \log \text{Det} R_{M_{1,r}} - \log \text{Det} R_{M_{2,r}}.$$  \hspace{1cm} (4.8)
Then a parameter family of trace class operators such that
$$\lim_{r \to 1} f_k(y) = \lambda_k f_k(y)$$
for \((u, y) \in N_{-r, 0}\),
$$\phi(u, y) = \begin{cases} (e^{\sqrt{\lambda_k} u} + \frac{e^{-\sqrt{\lambda_k} r}}{e^{\sqrt{\lambda_k} r} - e^{-\sqrt{\lambda_k} r}} (e^{\sqrt{\lambda_k} u} - e^{-\sqrt{\lambda_k} u})) f_k(y) \
\frac{e^{-\sqrt{\lambda_k} u} - \frac{e^{-\sqrt{\lambda_k} r}}{e^{\sqrt{\lambda_k} r} - e^{-\sqrt{\lambda_k} r}} (e^{\sqrt{\lambda_k} u} - e^{-\sqrt{\lambda_k} u})) f_k(y) \
\end{cases}$$
for \((u, y) \in N_{0, r}\).

Hence,
$$R_N, (f_k) = \left(2\sqrt{\lambda_k} + \frac{4\sqrt{\lambda_k} e^{-\sqrt{\lambda_k} r}}{e^{\sqrt{\lambda_k} r} - e^{-\sqrt{\lambda_k} r}}\right) f_k,$$
where we interpret \(\frac{4\sqrt{\lambda_k} e^{-\sqrt{\lambda_k} r}}{e^{\sqrt{\lambda_k} r} - e^{-\sqrt{\lambda_k} r}}\) as 0 when \(\lambda_k = 0\). The spectrum of \(R_N,\) is
$$\left\{2\sqrt{\lambda_k} + \frac{4\sqrt{\lambda_k} e^{-\sqrt{\lambda_k} r}}{e^{\sqrt{\lambda_k} r} - e^{-\sqrt{\lambda_k} r}} \mid \lambda_k \in \text{Spec}(\Delta_Y)\right\}.$$

Let \(P_{Ker \Delta_Y} : C^\infty(Y) \to C^\infty(Y)\) be the orthogonal projection onto \(\text{Ker} \Delta_Y\).

Then
$$\zeta_{R_N,}(s) - \zeta(2\sqrt{\Delta_Y} + 2 \frac{Ker \Delta_Y}{r}) (s) = \sum_{\lambda_k \neq 0} \left\{ \left(2\sqrt{\lambda_k} + \frac{4\sqrt{\lambda_k} e^{-\sqrt{\lambda_k} r}}{e^{\sqrt{\lambda_k} r} - e^{-\sqrt{\lambda_k} r}}\right)^{-s} - \left(2\sqrt{\lambda_k}\right)^{-s} \right\}.$$

The following lemma can be checked easily.

**Lemma 4.1.** Let \(A\) be an invertible elliptic operator of order \(> 0\), and \(K_r\) a one-parameter family of trace class operators such that \(\lim_{r \to \infty} Tr(K_r) = 0\). Then
$$\lim_{r \to \infty} \log \text{Det}(A + K_r) = \log \text{Det} A.$$

**Proof.** Note that
$$\log \text{Det}(A + K_r) - \log \text{Det} A = \int_0^1 \frac{d}{dt} \log \text{Det}(A + tK_r) dt = \int_0^1 Tr \left((A + tK_r)^{-1}K_r\right) dt.$$

If we denote by \(\lambda_0\) the smallest eigenvalue of \(|A|\), for \(r\) large enough we have
$$|\log \text{Det}(A + K_r) - \log \text{Det} A| \leq \frac{1}{2\lambda_0} Tr(K_r)$$
and hence the result follows. \(\square\)

Applying Lemma 4.1 with \(A = 2\sqrt{\Delta_Y}\) and \(K_r = g_r(\Delta_Y)\) with
$$g_r(x) = \frac{4\sqrt{x} e^{-\sqrt{x} r}}{e^{\sqrt{x} r} - e^{-\sqrt{x} r}}$$
on the orthogonal complement of \(\text{Ker} \Delta_Y\), we get the following equation:
$$\lim_{r \to \infty} \left\{ \log \text{Det} R_N, - \log \text{Det}(2\sqrt{\Delta_Y} + \frac{2}{r} P_{Ker \Delta_Y}) \right\} = 0.$$
Since
\[(4.9)\]
\[
\log \text{Det}(2\sqrt{\Delta_Y} + \frac{2}{r}P_{Ker\Delta_Y}) = \log 2 \cdot (\zeta_{\Delta_Y}(0) + \dim Ker\Delta_Y) + \frac{1}{2} \log \text{Det}\Delta_Y - (\dim Ker\Delta_Y) \log r,
\]
we get the following corollary.

**Corollary 4.2.**

\[
\lim_{r \to \infty} (\log \text{Det}R_{N_r} + (\dim Ker\Delta_Y) \log r) = \log 2 \cdot (\zeta_{\Delta_Y}(0) + \dim Ker\Delta_Y) + \frac{1}{2} \log \text{Det}\Delta_Y.
\]

Now we discuss the operators $R_{M_1,r}$, $R_{M_2,r}$ and $R_{-r,r}$. First, we can describe
\[
R_{M_1,r} : C^\infty(Y_r) \to C^\infty(Y_r)
\]
as follows. For $f_k \in C^\infty(Y_r)$ with $\Delta_Y f_k = \lambda_k f_k$, we choose the section $\phi \in C^0(M_{1,r})$ satisfying $\Delta_{M_{1,r}} \phi = 0$ on $M_{1,r} - Y_r$, $\phi|_{Y_r} = f_k$ and $\phi|_{\partial} = \phi|_{\partial Y_r} = 0$. Then one can check that
\[
R_{M_1,r}(f_k) = Q_1(f_k) - (\partial_u(\phi|_{N_{-r,0}}))|_{Y_r} = Q_1(f_k) + \left(\sqrt{\lambda_k} + \frac{2\sqrt{\lambda_k}e^{-\sqrt{\lambda_k}r}}{e^{\sqrt{\lambda_k}r} - e^{-\sqrt{\lambda_k}r}}\right) f_k.
\]
In the same way,
\[
R_{M_2,r}(f_k) = Q_2(f_k) + (\partial_u(\phi|_{N_0,0}))|_{Y_r} = Q_2(f_k) + \left(\sqrt{\lambda_k} + \frac{2\sqrt{\lambda_k}e^{-\sqrt{\lambda_k}r}}{e^{\sqrt{\lambda_k}r} - e^{-\sqrt{\lambda_k}r}}\right) f_k.
\]
Similarly, $R_{-r,r} : C^\infty(Y_r) \oplus C^\infty(Y_r) \to C^\infty(Y_r) \oplus C^\infty(Y_r)$ is described as follows:
\[
R_{-r,r}(f_k,0) = \left(Q_1(f_k) + \left(\sqrt{\lambda_k} + \frac{2\sqrt{\lambda_k}e^{-\sqrt{\lambda_k}r}}{e^{\sqrt{\lambda_k}r} - e^{-\sqrt{\lambda_k}r}}\right) f_k, -\frac{2\sqrt{\lambda_k}}{e^{2\sqrt{\lambda_k}r} - e^{-2\sqrt{\lambda_k}r}} f_k\right),
\]
\[
R_{-r,r}(0,f_k) = \left(-\frac{2\sqrt{\lambda_k}}{e^{2\sqrt{\lambda_k}r} - e^{-2\sqrt{\lambda_k}r}} f_k, Q_2(f_k) + \left(\sqrt{\lambda_k} + \frac{2\sqrt{\lambda_k}e^{-\sqrt{\lambda_k}r}}{e^{2\sqrt{\lambda_k}r} - e^{-2\sqrt{\lambda_k}r}}\right) f_k\right).
\]
We therefore have
\[
R_{-r,r} = \begin{pmatrix} Q_1 + \sqrt{\Delta_Y} & 0 \\ 0 & Q_2 + \sqrt{\Delta_Y} \end{pmatrix} + h_r(\Delta_Y) \begin{pmatrix} e^{-2r\sqrt{\Delta_Y}} & -1 \\ -1 & e^{-2r\sqrt{\Delta_Y}} \end{pmatrix},
\]
where $h_r(x) = \frac{2\sqrt{x}}{e^{2\sqrt{x}r} - e^{-2\sqrt{x}r}}$ and $h_r(\Delta_Y)$ acts on $\text{Ker}\Delta_Y$ as multiplication by $\frac{1}{r}$.

We are going to discuss the operators $Q_i$ and $Q_i + \sqrt{\Delta_Y}$. The following lemma can be checked by using integration by parts (cf. Proposition 4.3 in [2]).

**Lemma 4.3.** Suppose that $\nabla$ is a connection which is compatible to the inner product on $M$, i.e. for any sections $s_1, s_2 \in C^\infty(E)$ and a tangent vector $w$, $w(s_1, s_2) = (\nabla_w s_1, s_2) + (s_1, \nabla_w s_2)$. If $\Delta_M = \nabla^* \nabla$, then each $Q_i$ is a non-negative, self-adjoint operator.
Next, let us consider a Dirac Laplacian for a Dirac operator $A$ which has the form $G(\partial_a + B)$ near the boundary $Y$, where $G$ is a bundle automorphism satisfying the conditions (1.1), and both $G$ and $B$ do not depend on the normal coordinate $u$. We refer to [5] for the following lemma (cf. Lemma 3.1 in [5]).

**Lemma 4.4.** Let $\phi$ and $\psi$ be smooth sections on $M_j$ $(j = 1, 2)$. Then

$$\langle (A_{M_j} \phi, \psi)_{M_j} - \langle \phi, A_{M_j} \psi \rangle_{M_j} = \epsilon_j \langle \phi|_Y, G(\psi|_Y) \rangle_Y,$$

where $\epsilon_j = 1$ for $j = 2$ and $\epsilon_j = -1$ for $j = 1$.

Suppose that for $f \in C^\infty(Y)$, $\phi_j$ is the solution of $A^2_{M_j}$ with $\phi_j|_Y = f$, $\phi_j|_Z = 0$. Then by Lemma 4.4

$$\langle (Q_1 + |B|)f, f \rangle_Y = \langle A_{M_1} \phi_1, A_{M_1} \phi_1 \rangle_{M_1} + \langle (|B| - B)f, f \rangle_Y, \tag{4.10}$$

$$\langle (Q_2 + |B|)f, f \rangle_Y = \langle A_{M_2} \phi_2, A_{M_2} \phi_2 \rangle_{M_2} + \langle (|B| + B)f, f \rangle_Y. \tag{4.11}$$

As a consequence, $f \in \text{Ker}(Q_1 + |B|)$ if and only if $A_{M_1} \phi_1 = 0$ and $f \in \text{Im}P_\geq$; and hence on the cylinder part we can express $\phi_1$ as

$$\phi_1 = \sum_{j=1}^k a_j g_j + \sum_{\lambda_j > 0} b_j e^{-\lambda_j u} h_j,$$

where $Bg_j = 0$, $Bh_j = \lambda_j h_j$. This implies that $\phi_1$ is the restriction of an extended $L^2$-solution of $A_{M_{1,\infty}}$ on $M_{1,\infty} := M_1 \cup_Y Y \times [0, \infty)$. We can make a similar assertion for $\phi_2$ and have the following corollary (cf. Theorem 2.2 in [5], see also [1, 2]).

**Corollary 4.5.** The invertibility of $Q_1 + \sqrt{B^2}$ and $Q_2 + \sqrt{B^2}$ is equivalent to the non-existence of the extended $L^2$-solutions of $A_{M_{1,\infty}}$ and $A_{M_{2,\infty}}$ on $M_{1,\infty}$ and $M_{2,\infty}$. In particular, this condition implies that $\text{Ker}B = 0$.

**Lemma 4.6.** Suppose that $\Delta_M$ is either a connection Laplacian or a Dirac Laplacian for a connection compatible to the inner product as above, and $\Delta_{M, D}$ is invertible. If both $Q_1 + \sqrt{\Delta_Y}$ and $Q_2 + \sqrt{\Delta_Y}$ are invertible, then $R_{-r, r}$ and $\Delta_{M, D}$ are invertible for $r$ large enough.

**Proof.** We are going to show first that $R_{-r, r}$ is injective. Then this implies that $\Delta_{M, D}$ is injective. Since $\Delta_{M, D}$ is self-adjoint, $\Delta_{M, D}$ is invertible, and this implies again that $R_{-r, r}$ is also invertible ([2], [3]).

Putting $A_r = h_r(\Delta_Y)$ with $h_r(x) = \frac{2\sqrt{r}}{e^{2\sqrt{r}x} - e^{-2\sqrt{r}x}}$, we get

$$\langle R_{-r, r} f, g \rangle_{L^2(Y)} = \langle (Q_1 + \sqrt{\Delta_Y})f, f \rangle_Y + \langle (Q_2 + \sqrt{\Delta_Y})g, g \rangle_Y$$

$$+ \langle A_r e^{-2r\sqrt{\Delta_Y}} f, f \rangle + \langle A_r e^{-2r\sqrt{\Delta_Y}} g, g \rangle - \langle A_r f, f \rangle - \langle A_r g, g \rangle.$$

Note that each $Q_1 + \sqrt{\Delta_Y}$ is a non-negative operator by Lemma 4.3 and (4.10), (4.11). Let $\lambda_0$ be the minimum of the eigenvalues of $Q_1 + \sqrt{\Delta_Y}$ and $Q_2 + \sqrt{\Delta_Y}$. Since $\lim_{r \to \infty} ||A_r||_{L^2} = 0$, one can choose $r_0$ so that $||A_r||_{L^2} < \lambda_0$ for $r \geq r_0$. Then $R_{-r, r}$ is injective for $r \geq r_0$ and this completes the proof. \qed
In case both \( Q_1 + \sqrt{\Delta_Y} \) and \( Q_2 + \sqrt{\Delta_Y} \) are invertible, we can apply Lemma 4.1 directly.

**Corollary 4.7.** Assume that both \( Q_1 + \sqrt{\Delta_Y} \) and \( Q_2 + \sqrt{\Delta_Y} \) are invertible. Then:

1. \( \lim_{r \to \infty} \log \operatorname{Det} R_{M_1, r} = \log \operatorname{Det}(Q_1 + \sqrt{\Delta_Y}) \).
2. \( \lim_{r \to \infty} \log \operatorname{Det} R_{M_2, r} = \log \operatorname{Det}(Q_2 + \sqrt{\Delta_Y}) \).
3. \( \lim_{r \to \infty} \log \operatorname{Det} R_{-r, r} = \log \operatorname{Det}(Q_1 + \sqrt{\Delta_Y}) + \log \operatorname{Det}(Q_2 + \sqrt{\Delta_Y}) \).

Combining Corollary 4.2 with Corollary 4.7 and (4.2), (4.8), we complete the proof of Theorem 1.4.

5. The adiabatic decomposition of the analytic torsion

In this section, we are going to prove Theorem 1.6 and Theorem 1.7. Recall that \( M \) is a closed manifold of dimension \( m \) with the product structure near a hypersurface \( Y \). We define \( M_r, M_{1, r} \) and \( M_{2, r} \) as in Section 4 and suppose that \( \rho_{M_r} (\rho_{M_{1, r}}, \ \rho_{M_{2, r}}, \ \rho_Y) \) is an orthogonal representation of \( \pi_1(M_r) \ (\pi_1(M_{1, r}), \ \pi_1(M_{2, r}), \ \pi_1(Y)) \) to \( SO(n) \), respectively. Then we can construct a flat bundle \( E_{\rho_{M_r}} = M_r \times_{\rho_{M_r}} \mathbb{R}^n \), where \( \tilde{M}_r \) is the universal cover of \( M_r \). The flat bundles \( E_{\rho_{M_{1, r}}}, E_{\rho_{M_{2, r}}} \) and \( E_{\rho_Y} \) are defined in the same way.

For each \( q \), denote by \( \Delta_{M_r}^q := (d_q + d_q^*)^2 \) the Hodge Laplacian acting on \( q \)-forms valued in \( E_{\rho_{M_r}} \). Then the analytic torsion \( \tau(M_r, \rho_{M_r}) \) is defined by

\[
\log \tau(M_r, \rho_{M_r}) = \frac{1}{2} \sum_{q=0}^{m} (-1)^q \cdot q \cdot \log \operatorname{Det} \Delta_{M_r}^q.
\]

To define the analytic torsion on \( M_{i, r} \), we choose the absolute or the relative boundary condition on \( Y_0 \). Near \( Y_0 \), a differential \( q \)-form \( \omega \) can be expressed by

\[
\omega = \omega_1 + du \wedge \omega_2,
\]

where \( \omega_1 \) and \( \omega_2 \) do not contain \( du \).

**Definition 5.1.** Suppose that a \( q \)-form \( \omega \) in \( M_{1, r} \) is expressed as in (5.1).

1. \( \omega \) satisfies the absolute boundary condition if \( (\partial_u \omega_1)|_{Y_0} = 0 \) and \( \omega_2|_{Y_0} = 0 \).
2. \( \omega \) satisfies the relative boundary condition if \( \omega_1|_{Y_0} = 0 \) and \( (\partial_u \omega_2)|_{Y_0} = 0 \).

We denote by \( \Omega_{abs}^q(M_{1, r}) \), \( \Omega_{rel}^q(M_{1, r}) \) the sets of all \( q \)-forms valued in \( E_{M_{1, r}} \) satisfying the absolute and the relative boundary conditions, respectively. We also denote by \( \Delta_{M_{1, r}, abs}^q \), \( \Delta_{M_{1, r}, rel}^q \) the Laplacian acting on \( q \)-forms valued in \( E_{M_{1, r}} \) with

\[
\operatorname{Dom}(\Delta_{M_{1, r}, abs}^q) = \Omega_{abs}^q(M_{1, r}), \quad \operatorname{Dom}(\Delta_{M_{1, r}, rel}^q) = \Omega_{rel}^q(M_{1, r}).
\]

Then the analytic torsions \( \tau_{abs}(M_{i, r}, \rho_{M_{i, r}}) \) and \( \tau_{rel}(M_{i, r}, \rho_{M_{i, r}}) \) are defined by

\[
\log \tau_{abs}(M_{i, r}, \rho_{M_{i, r}}) = \frac{1}{2} \sum_{q=0}^{m} (-1)^q \cdot q \cdot \log \operatorname{Det} \Delta_{M_{i, r}, abs}^q,
\]

\[
\log \tau_{rel}(M_{i, r}, \rho_{M_{i, r}}) = \frac{1}{2} \sum_{q=0}^{m} (-1)^q \cdot q \cdot \log \operatorname{Det} \Delta_{M_{i, r}, rel}^q.
\]

It is a well-known fact (cf. [11]) that

\[
\ker \Delta_{M_{1, r}, abs}^q \cong H^q(M_{1, r}; \rho_{M_{1, r}}), \quad \ker \Delta_{M_{1, r}, rel}^q \cong H^q(M_{1, r}; Y; \rho_{M_{1, r}}).
\]
We consider $M_{1,r}$ (a manifold with boundary $Y$) first. Recall that $M_{1,r} = M_1 \cup_{Y_{-r}} N_{-r,0}$ with $Y_{-r} = [-r,0] \times Y$, and $Y_{-r} = \{-r\} \times Y$, $Y_0 = \{0\} \times Y$. We denote by $B$, $D$ the Dirichlet boundary conditions on $Y_{-r}$, $Y_0$, respectively.

For a given representation $\rho_{M_{1,r}} : \pi_1(M_{1,r}) \to SO(n)$, define $\rho_Y : \pi_1(Y) \to SO(n)$ by $\rho_Y = \rho_{M_{1,r}} \circ \iota_Y$, where $\iota_Y : \pi_1(Y) \to \pi_1(M_{1,r})$ is the natural homomorphism. Then the restriction of the bundle $E_{\rho_{M_{1,r}}}$ to $Y$ is isomorphic to $E_{\rho_Y}$, (cf. [1]).

The set $\Omega^q(N_{-r,0}, E_{\rho_{M_{1,r}}}|_{N_{-r,0}})$ of $q$-forms valued in $E_{\rho_{M_{1,r}}}|_{N_{-r,0}}$ can be decomposed as follows:

\[
\Omega^q(N_{-r,0}, E_{\rho_{M_{1,r}}}|_{N_{-r,0}}) = C^\infty([-r,0], E_{\rho_{M_{1,r}}}|_{N_{-r,0}}) \otimes \Omega^q(Y, E_{\rho_Y})
\]

\[
\oplus du \wedge C^\infty([-r,0], E_{\rho_{M_{1,r}}}|_{N_{-r,0}}) \otimes \Omega^{q-1}(Y, E_{\rho_Y}).
\]

From this decomposition, the Laplacian $\Delta_Y^q$, when restricted to $N_{-r,0}$, can be expressed as

\[
\Delta_Y^q = -\partial_u^2 + \begin{pmatrix} \Delta_Y & 0 \\ 0 & \Delta_Y^{q-1} \end{pmatrix},
\]

where $\Delta_Y$ is the Laplacian acting on $q$-forms on $Y$, valued in $E_{\rho_Y}$. Here and throughout this section we use the convention that $\Delta_Y^q = 0$ for $q < 0$ or $q \geq m$.

To describe the gluing formula of the type of Theorem 1.1 (or Corollary 1.3) in this context, we need to define modified Dirichlet-to-Neumann operators $Q_Y^q$, $Q_{N_{-r,0}}^{q,abs}$ and $Q_{N_{-r,0}}^{q,rel}$ as follows. For simplicity, set $E = \bigwedge^q T^*M_{1,r} \otimes E_{\rho_{M_{1,r}}}$. For a given $f \in C^\infty(E|_{Y_{-r}})$, choose smooth sections $\phi \in C^\infty(E|_{M_1})$, $\psi_{abs} \in C^\infty(E|_{N_{-r,0}})$ and $\psi_{rel} \in C^\infty(E|_{N_{-r,0}})$ such that

\[
\Delta_{M_1}^q \phi = 0, \quad \Delta_{N_{-r,0}}^q \psi_{abs} = \Delta_{N_{-r,0}}^q \psi_{rel} = 0, \quad \phi|_{Y_{-r}} = \psi_{abs}|_{Y_{-r}} = \psi_{rel}|_{Y_{-r}} = f,
\]

and $\psi_{abs}$ ($\psi_{rel}$) satisfies the absolute (relative) boundary condition on $Y_0$, respectively. Then we define

\[
Q_Y^q(f) = (\partial_u \phi)|_{Y_{-r}},
\]

\[
Q_{N_{-r,0}}^{q,abs}(f) = (\partial_u \psi_{abs})|_{Y_{-r}}, \quad Q_{N_{-r,0},rel}^q(f) = (\partial_u \psi_{rel})|_{Y_{-r}},
\]

and

\[
R_{B,abs}^q = Q_Y^q + Q_{N_{-r,0},abs}^q, \quad R_{B,rel}^q = Q_Y^q + Q_{N_{-r,0},rel}^q.
\]

Then the following theorem can be proved in the same way as Theorem 1.1 (cf. the Remark after Corollary 1.3).

**Theorem 5.2.** We denote $k_q = \dim \ker \Delta_Y^q$. Then:

1. $\log \det \Delta_{M_{1,r},D}^q - \log \det \Delta_{M_{1,B}}^q - \log \det \Delta_{N_{r,0},B,D}^q = -\log (\zeta_{\Delta_Y^q}(0) + \zeta_{\Delta_Y^q}(0) + k_{q-1} + k_q) + \log \det R_{B,D}^q$.

2. $\log \det \Delta_{M_{1,r},abs}^q - \log \det \Delta_{M_{1,B}}^q - \log \det \Delta_{N_{-r,0},abs}^q = -\log (\zeta_{\Delta_Y^q}(0) + \zeta_{\Delta_Y^q}(0) + k_{q-1} + k_q) + \log \det R_{B,abs}^q$.

3. $\log \det \Delta_{M_{1,r},rel}^q - \log \det \Delta_{M_{1,B}}^q - \log \det \Delta_{N_{-r,0},rel}^q = -\log (\zeta_{\Delta_Y^q}(0) + \zeta_{\Delta_Y^q}(0) + k_{q-1} + k_q) + \log \det R_{B,rel}^q$. 


We next describe the operators $\Delta^q_{_{N-r,0,B,\text{abs}}}$ and $\Delta^q_{_{N-r,0,B,\text{rel}}}$. From the decomposition (5.2), we have

$$
\Delta^q_{_{N-r,0,B,\text{abs}}} = \begin{pmatrix} \Delta^q_{_{N-r,0,B,C}} & 0 \\ -\partial^2_u + \Delta^q_{_{N-r,0,B,D}} & -\partial^2_u + \Delta^q_{_{N-r,0,B,D}}^{-1} \end{pmatrix},
$$

$$
\Delta^q_{_{N-r,0,B,\text{rel}}} = \begin{pmatrix} \Delta^q_{_{N-r,0,B,C}} & 0 \\ -\partial^2_u + \Delta^q_{_{N-r,0,B,D}} & -\partial^2_u + \Delta^q_{_{N-r,0,B,D}}^{-1} \end{pmatrix},
$$

where $C$ means the Neumann boundary condition on $Y$ and $B$ (D) means the Dirichlet boundary condition on $Y_r$ ($Y_0$). Hence, we have

$$(5.4) \quad \log \det \Delta^q_{_{N-r,0,B,\text{abs}}} - \log \det \Delta^q_{_{N-r,0,B,D}} = \log \det(-\partial^2_u + \Delta^q_{_{N-r,0,B,C}}) - \log \det(-\partial^2_u + \Delta^q_{_{N-r,0,B,D}}),$$

$$(5.5) \quad \log \det \Delta^q_{_{N-r,0,B,\text{rel}}} - \log \det \Delta^q_{_{N-r,0,B,D}} = \log \det(-\partial^2_u + \Delta^q_{_{N-r,0,B,C}}) - \log \det(-\partial^2_u + \Delta^q_{_{N-r,0,B,D}}).$$

Now we assume that $Q_1^q + \left( \begin{array}{cc} \sqrt{\Delta^q} & 0 \\ \frac{1}{\sqrt{\Delta^q}} & 0 \end{array} \right)$ is invertible. Since the Hodge Laplacian $\Delta^q_{_{M_r}}$ is a Dirac Laplacian satisfying (1.1), by Corollary 4.5 we have $k_{q-1} = k_q = 0$ (cf. the Remark below Theorem 1.6). By Corollary 1.5 and (5.4), (5.5) we have

$$(5.6) \quad \lim_{r \to \infty} \left\{ \log \det \Delta^q_{_{N-r,0,B,\text{abs}}} - \log \det \Delta^q_{_{N-r,0,B,D}} \right\} = \frac{1}{2} \log \det \Delta^q_{_{Y}},$$

$$(5.7) \quad \lim_{r \to \infty} \left\{ \log \det \Delta^q_{_{N-r,0,B,\text{rel}}} - \log \det \Delta^q_{_{N-r,0,B,D}} \right\} = \frac{1}{2} \log \det \Delta^q_{_{Y}}^{-1}.$$
The case of \( \log \text{Det} R^q_{B, \text{rel}} \) can be proved in the same way.

By a direct computation one can check the following. For \( f \in \Omega^q(Y, E_{\rho_Y}) \) with \( \Delta^q_Y f = \lambda f \),

\[
R^q_{B, \text{abs}}(f) = Q^q_1(f) + \left( \sqrt{\lambda} - \frac{2\sqrt{\lambda e^{-\sqrt{\lambda r}}}}{e^{\sqrt{\lambda r}} + e^{-\sqrt{\lambda r}}} \right) f.
\]

For \( g \in \Omega^{q-1}(Y, E_{\rho_Y}) \) with \( \Delta^{q-1}_Y g = \mu g \),

\[
R^q_{B, \text{abs}}(du \wedge g) = Q^q_1(du \wedge g) + \left( \sqrt{\mu} + \frac{2\sqrt{\mu e^{-\sqrt{\mu r}}}}{e^{\sqrt{\mu r}} - e^{-\sqrt{\mu r}}} \right) du \wedge g.
\]

Then the result follows from Lemma 4.1.

From (5.6)–(5.9) and Lemma 5.3, we have the following corollary.

**Corollary 5.4.** Suppose that \( Q^q_1 \left( \begin{bmatrix} \sqrt{\lambda} & 0 \\ 0 & \sqrt{\lambda^{-1}} \end{bmatrix} \right) \) is invertible for each \( q \). Then the following equalities hold:

1. \[
\lim_{r \to \infty} \left\{ \log \text{Det} \Delta^q_{M_1, r, \text{abs}} - \log \text{Det} \Delta^q_{M_1, r, \text{D}} \right\} = \begin{cases} \frac{1}{2} \log \text{Det} \Delta^q_Y & (0 < q < m - 1), \\ 0 & (q = m). \end{cases}
\]

2. \[
\lim_{r \to \infty} \left\{ \log \text{Det} \Delta^q_{M_1, r, \text{rel}} - \log \text{Det} \Delta^q_{M_1, r, \text{D}} \right\} = \begin{cases} \frac{1}{2} \log \text{Det} \Delta^{q-1}_Y & (1 < q < m), \\ 0 & (q = 0). \end{cases}
\]

Now we are ready to prove Theorem 1.6. We have

\[
\lim_{r \to \infty} \left\{ \log \tau_{\text{abs}}(M_1, \rho_{M_1}) - \log \tau_{\text{rel}}(M_1, \rho_{M_1}) \right\} = \lim_{r \to \infty} \frac{1}{2} \sum_{q=0}^{m} (-1)^q \cdot q \cdot (\log \text{Det} \Delta^q_{M_1, r, \text{abs}} - \log \text{Det} \Delta^q_{M_1, r, \text{D}})
\]

\[
- \lim_{r \to \infty} \frac{1}{2} \sum_{q=0}^{m} (-1)^q \cdot q \cdot (\log \text{Det} \Delta^q_{M_1, r, \text{rel}} - \log \text{Det} \Delta^q_{M_1, r, \text{D}})
\]

\[
= \frac{1}{4} \sum_{q=0}^{m-1} (-1)^q \cdot q \cdot \log \text{Det}(\Delta^q_Y) - \frac{1}{4} \sum_{q=1}^{m} (-1)^q \cdot q \cdot \log \text{Det}(\Delta^{q-1}_Y)
\]

\[
= \frac{1}{2} \sum_{q=0}^{m-1} (-1)^q \cdot q \cdot \log \text{Det}(\Delta^q_Y) + \frac{1}{4} \sum_{q=0}^{m-1} (-1)^q \cdot q \cdot \log \text{Det}(\Delta^q_Y)
\]

\[
= \tau(Y, \rho_Y).
\]

This completes the proof of Theorem 1.6. \( \square \)

Next, we take care of the closed manifold \( M_r = M_{1, r} \cup Y_0 M_{2, r} \). From Theorem 1.4, we have

\[
\lim_{r \to \infty} \left\{ \log \text{Det} \Delta^q_{M_r} - \log \text{Det} \Delta^q_{M_{1, r}, \text{D}} - \log \text{Det} \Delta^q_{M_{2, r}, \text{D}} \right\} = \frac{1}{2} \left( \log \text{Det} \Delta^q_Y + \log \text{Det} \Delta^{q-1}_Y \right).
\]
On the other hand,
\[
\lim_{r \to \infty} \left\{ \log \text{Det} \Delta_{M_r}^q - \log \text{Det} \Delta_{M_{1,r},D}^q - \log \text{Det} \Delta_{M_{2,r},D}^q \right\} \\
= \lim_{r \to \infty} \left\{ \left( \log \text{Det} \Delta_{M_r}^q - \log \text{Det} \Delta_{M_{1,r},\text{abs}}^q - \log \text{Det} \Delta_{M_{2,r},\text{rel}}^q \right) \\
+ \left( \log \text{Det} \Delta_{M_{1,r},\text{abs}}^q - \log \text{Det} \Delta_{M_{1,r},D}^q \right) \\
+ \left( \log \text{Det} \Delta_{M_{2,r},\text{rel}}^q - \log \text{Det} \Delta_{M_{2,r},D}^q \right) \right\}.
\]

From Corollary 5.4 we have
\[
\lim_{r \to \infty} \left\{ \log \text{Det} \Delta_{M_r}^q - \log \text{Det} \Delta_{M_{1,r},\text{abs}}^q - \log \text{Det} \Delta_{M_{2,r},\text{rel}}^q \right\} = 0,
\]
and therefore we obtain
\[
\lim_{r \to \infty} \left\{ \sigma(M_r, \rho_{M_r}) - \sigma_{\text{abs}}(M_{1,r}, \rho_{M_{1,r}}) - \sigma_{\text{rel}}(M_{2,r}, \rho_{M_{2,r}}) \right\} = 0,
\]
which completes the proof of Theorem 1.7.

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