THE GROMOV-LAWSON-ROSENBERG CONJECTURE FOR COCOMPACT FUCHSIAN GROUPS

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Abstract. We prove the Gromov-Lawson-Rosenberg conjecture for cocompact Fuchsian groups, thereby giving necessary and sufficient conditions for a closed spin manifold of dimension greater than four with fundamental group cocompact Fuchsian to admit a metric of positive scalar curvature.

Given a smooth closed manifold $M^n$, it is a long-standing question to determine whether or not $M$ admits a Riemannian metric of positive scalar curvature. Work of Gromov-Lawson and Schoen-Yau shows that if $N^n$ admits positive scalar curvature and $M$ is obtained from $N$ by $k$-surgeries of codimension $n-k \geq 3$, then $M$ admits positive scalar curvature as well. In the case when $M$ is spin, this surgery result implies the following.

Bordism Theorem. (10, 27) Let $M^n$ be a closed spin manifold, $n \geq 5$, $G = \pi_1(M)$, and suppose $u : M \to BG$ induces the identity on the fundamental group. If there is a positively scalar curved spin manifold $N^n$ and a map $v : N \to BG$ such that $[M,u] = [N,v] \in \Omega_{n}^{\text{Spin}}(BG)$, then $M$ admits a metric of positive scalar curvature.

On the other hand, the work of Lichnerowicz gives an obstruction to manifolds admitting positive scalar curvature. Using the Weitzenböck formula for the Dirac operator and the Atiyah-Singer index theorem, he proves in [18] that if $M^{4k}$ is a closed spin manifold with positive scalar curvature then $\hat{A}(M)$, the $A$-hat genus of $M$, vanishes. Generalizations of the Dirac operator and its index by Hitchin [12] and Miščenko-Fomenko [20] provide obstructions as well, taking final form in the following theorem of Rosenberg [23].

Obstruction Theorem. [23, 29] Let $M^n$ be a closed spin manifold and $u : M \to BG$ be a continuous map for some discrete group $G$. If $M$ admits a metric of positive scalar curvature then $\alpha[M,u] = 0$ in $KO_n(C^*_rG)$, where $\alpha : \Omega^{\text{Spin}}_n(BG) \to KO_n(C^*_rG)$ is the index of the Dirac operator.

Here $C^*_rG$ is the reduced real $C^*$-algebra of $G$, a suitable completion of the group algebra $RG$. In dimensions $4k$ with $G = 1$, the index $\alpha[M,u]$ agrees with $\hat{A}(M)$ up to a constant factor (17, p. 149). The above theorem motivates

The Gromov-Lawson-Rosenberg (GLR) Conjecture for $G$. Let $M^n$ be a closed spin manifold, $n \geq 5$, $G = \pi_1(M)$, and suppose $u : M \to BG$ induces the

2000 Mathematics Subject Classification Primary: 53C21. Secondary: 19L41, 19L64, 57R15, 55N15, 53C20.

Key words and phrases: positive scalar curvature, $K$-theory, Fuchsian groups.
identity on the fundamental group. Then $M$ admits positive scalar curvature if and only if $\alpha[M, U]$ is zero in $KO_n(C^*_r G)$.

The conjecture has been verified in the cases when $G$ is trivial $\mathbb{Z}^2$, $\mathbb{Z}/2$ $\mathbb{Z}/n$ for $n$ odd $\mathbb{Z}/2$, $\mathbb{Z}/n$ for $n$ odd $\mathbb{Z}/2$ $\mathbb{Z}/n$, has periodic cohomology $\mathbb{Z}$ $\mathbb{Z}/16$, or is one of certain elementary abelian groups $\mathbb{Z}$. Infinite groups for which the conjecture is proven are free and free abelian groups $\mathbb{Z}$, certain other torsion-free groups $\mathbb{Z}$, and some crystallographic groups with prime torsion $\mathbb{Z}$. However, in $\mathbb{Z}$, Schick shows the conjecture is false for $\mathbb{Z}$ and the conjecture holds after crossing $\mathbb{Z}$, and as such they have rich geometric properties (see $\mathbb{Z}$ as a reference). Each cocompact Fuchsian group is classified by its signature, $(g; v_1, v_2, \ldots, v_r)$, where $g$ is the genus of the compact orbit space $\mathbb{H}^2/\Gamma$ and $\mathbb{Z}/\nu_j$ is the stabilizer of a lift $\tilde{v}_j$ of a singular point $v_j \in \mathbb{H}^2/\Gamma$ of the branched covering $\mathbb{H}^2 \to \mathbb{H}^2/\Gamma$. The group $\Gamma$ has $r$ conjugacy classes of maximal finite subgroups, all of which are cyclic. The integers $\nu_i$ indicate their order. Furthermore, nearly all signatures $(g; v_1, v_2, \ldots, v_r)$ are realizable: if $\nu_j \geq 2, g \geq 0, r \geq 0$ and $2g - 2 + \Sigma(1 - 1/\nu_j) > 0$, then there exists a Fuchsian group $\Gamma$ with this signature. Generators and relations for $\Gamma$ were found by Poincaré $\mathbb{Z}$ (a more modern reference is $\mathbb{Z}$),

$$\Gamma = \langle a_1, b_1, \ldots a_g, b_g, c_1, \ldots c_r \mid [a_1, b_1] \cdots [a_g, b_g] = c_1 \cdots c_r, c_1^{\nu_1} = \cdots = c_r^{\nu_r} = 1 \rangle.$$ We can now formally state our

**Main Theorem.** The Gromov-Lawson-Rosenberg conjecture is true for all cocompact Fuchsian groups.

Following the general line of proof in $\mathbb{Z}$, our strategy is to use the validity of Baum-Connes conjecture for the group $\Gamma$ and the $p$-chain spectral sequence to understand the map $\alpha$ by studying how it factors through connective and periodic real $K$-theory, and then to exploit the fact that the Gromov-Lawson-Rosenberg conjecture is true for each finite subgroup of $\Gamma$.

## 1. Assorted Definitions

A real $C^*$-algebra is a real Banach $*$-algebra $A$ which is $*$-isomorphic to a norm-closed subalgebra of the bounded operators $B(H)$ on a real Hilbert space $H$. An example of such is given by the reduced $C^*$-algebra $C^*_r G$ of a discrete group $G$, which is defined to the closure of $\mathbb{R}G$ in $B(\ell^2(G))$, where $\mathbb{R}G$ acts on $\ell^2(G)$ by multiplication.

For a $C^*$-algebra $A$ with unit, and for $n > 0$, define $KO_n(A) = \pi_{n-1}(GL(A))$. There is the Bott map, defined using Clifford algebras, $GL(A) \to \Omega^8(GL(A))$, which, according to Bott periodicity $\mathbb{Z}$, is a homotopy equivalence. Then for any $n$, define $KO_n(A) = \pi_{n+8k-1}(GL(A))$, where $n + 8k > 0$. One can show $KO_0(A)$ is the Grothendieck group of isomorphism classes of finitely generated projective
categories, in other words, the algebraic $K_0$ of the ring $A$. For more details on $C^*$-algebras and their $K$-theory we refer the reader to [17].

The above theory is sufficient for analysis, but to compute using algebraic topology one needs spectra. By a spectrum $K$, we mean an sequence of based spaces $\{K_n\}_{n \geq 0}$ and based maps $\sigma_n : SK \rightarrow K_{n+1}$, where $S$ denotes suspension. A map of spectra $f : K \rightarrow K'$ is a sequence of based maps $f_n : K_n \rightarrow K'_n$ commuting with the structure maps, i.e. $f_{n+1}' \circ \sigma_n = \sigma_n' \circ f_n$. For a real $C^*$-algebra with unit $A$, define the Bott spectrum $KO(A)$ to have as its $n$-th space $\Omega^i(GL(A))$ where $i \in \{0,1,2, \ldots,7\}$ and $i+n+1 \equiv 0 \pmod{8}$. Most of the structure maps $S\Omega^i(GL(A)) \rightarrow \Omega^{i-1}(GL(A))$ are given as the adjoint of the identity map on $\Omega^i(GL(A))$, while one-eighth of the maps are given by the adjoint of the Bott map. Then $\pi_n(KO(A)) = KO_n(A)$ for all $n \in \mathbb{Z}$. We will write $KO$ for $KO(\mathbb{R})$.

However, the above spectra are still insufficient for our purposes. A preliminary problem is that the fundamental group depends on a choice of base point, but a much more severe problem is that $\pi_0$ is not a functor from the category of based spaces, since the reduced $C^*$-algebra of a group is not functorial for group homomorphisms with infinite kernel. This obstructs both a definition of the assembly map in terms of algebraic topology and an axiomatic characterization of the assembly map, both of which are necessary in this paper.

These base point and functorial problems can be avoided by the use of $C^*$-categories, which is the point of view of [5]. In this paper we will need a composite of three functors

$$Or(G) \rightarrow \text{GROUPOIDS}^{\text{proper}} \rightarrow C^*\text{-CATEGORIES} \rightarrow \text{SPECTRA}$$

which we describe from right to left. A $C^*$-category $A$ is a category, so that for any two objects $c, d$, the morphism set $\text{mor}_A(c, d)$ is a Banach space with an involution $\ast : \text{mor}_A(c, d) \rightarrow \text{mor}_A(d, c)$ satisfying the expected properties (e.g. bilinearity with respect to composition), and so that for all $f \in \text{mor}_A(c, d)$, $\|f \circ f\| = \|f\|^2$ and so that $f^* \circ f$ has non-negative spectrum (in the sense of analysis). A $C^*$-category is a topological category: the morphisms sets are topological spaces, although in this case the objects are discrete. A $C^*$-category with exactly one object is a $C^*$-algebra. The category $C^*\text{-CATEGORIES}$ is the category of all small (i.e. the objects form a set) $C^*$-categories. The functor $F : C^*\text{-CATEGORIES} \rightarrow \text{SPECTRA}$ is to have two properties: when the $C^*$-category has a single object, one gets the Bott spectrum and and an equivalence of $C^*$-categories gives a homotopy equivalence of spectra. Unfortunately, the construction of $F$ in [5] was flawed by failing to heed the warning of [30]; the problem can be repaired without a great deal of difficulty using Segal’s $\Gamma$-spaces. Alternatively, such a functor has been constructed in [19].

A (discrete) groupoid $G$ is a category all of whose morphisms are isomorphisms; a groupoid with a single object is a group. Associated to a groupoid $G$ is a $C^*$-category $C^*_r(G)$, whose objects are the same as those of $G$, and whose morphisms are given by the closure of the linear span of $\text{mor}_G(c, d) \subset B(\ell^2(\text{mor}_G(c, c)), \ell^2(\text{mor}_G(c, d)))$. A morphism of groupoids is a functor; a morphism $F : G_1 \rightarrow G_2$ is proper if for all objects $c$ and $d$ of $G_1$, there is a $n = n(c, d)$ so that for all $f \in \text{mor}_{G_1}(F(c), F(d))$, $F^{-1}(f) \subset \text{mor}_{G_1}(c, d)$ has cardinality less than $n$. A proper morphism between groupoids induces a map of the associated $C^*$-categories. This gives our functor from
The composite functor 

\[
\text{KO}^{\text{top}} : \text{Or}(G) \to \text{SPECTRA},
\]

satisfies \(\pi_n \text{KO}^{\text{top}}(G/H) = KO_n(C^*_r H)\). This functor is, according to [5], the basic building block of the assembly map (of which there are four equivalent descriptions in [29]). Give a family \(\mathcal{F}\) of subgroups of \(G\), define the restricted orbit category \(\text{Or}(G, \mathcal{F})\) to be the full subcategory of \(\text{Or}(G)\) whose objects are \(G/H\) with \(H \in \mathcal{F}\). Let 1 denote the family consisting of the trivial subgroup and \(\mathcal{F}\) in the family of finite subgroups. Consider the maps

\[
BG_+ \wedge KO \simeq \text{hocolim} \text{KO}^{\text{top}} \to \text{hocolim} \text{KO}^{\text{top}} \to \text{hocolim} \text{KO}^{\text{top}} \simeq KO(C^*_r G)
\]

The assembly map \(KO_n(BG) \to KO_n(C^*_r(G))\) is, by definition, \(\pi_n\) applied to the composite. The induced map

\[
\pi_n(\text{hocolim} \text{KO}^{\text{top}}) \to KO_n(C^*_r(G))
\]

has been identified with the Baum-Connes map in [11]. This identification is crucial for us, because the analytic map gives the obstructions to positive scalar curvature, and the topological map we need for computations.

2. Proof of the Main Theorem

Recall [29] that \(\alpha\) is the composition \(\alpha = A \circ p \circ D\),

\[
\Omega^\text{Spin}_n(BG) \xrightarrow{D} ko_n(BG) \xrightarrow{p} KO_n(BG) \xrightarrow{A} KO_n(C^*_r G).
\]

Here \(D\) is the \(ko\)-orientation of spin bordism, \(p\) is the covering of periodic \(K\)-theory by connective \(K\)-theory, and \(A\) is the assembly map. The groups \(ko_n(*) = 0\) for \(n < 0\) and \(p : ko_n(*) \to KO_n(*)\) is an isomorphism for \(n \geq 0\).

The utility of this factorization is the generalization of the Bordism Theorem by Jung and Stolz. Let \(ko^*_n(BG)\) be the subgroup of \(ko_n(BG)\) given by \(D[N^n, v]\) where \(N\) is a positively curved spin manifold and \(v : N \to BG\) is a continuous map.

**Theorem 1.** [29] Let \(M^n\) be a closed spin manifold, \(n \geq 5\), \(G = \pi_1(M)\), and suppose \(u : M \to BG\) induces the identity on the fundamental group. If \(D[M, u] \in ko^*_n(BG)\), then \(M\) admits a metric of positive scalar curvature.

Our direct sum in the theorem below and hereafter will be over the \(r\) conjugacy classes \((C)\) of maximal finite subgroups of \(\Gamma\). Thus \(C \cong \mathbb{Z}/\nu_j\) for \(j = 1, \ldots, r\).
Proposition 2. Let $\Gamma$ be a cocompact Fuchsian group with signature $(g; \nu_1, \nu_2, \ldots, \nu_r)$ and $E$ be any covariant functor from $\text{Or}(\Gamma, \mathcal{F}\text{in})$ to $\text{SPECTRA}$. Then there is an exact sequence
\[
\cdots \to \oplus_{(C)} H_n(BC; E(\Gamma/1)) \to (\oplus_{(C)} \pi_n(E(\Gamma/C))) \oplus H_n(B\Gamma; E(\Gamma/1)) \to \pi_n(\text{hocolim}_E E) \to (\oplus_{(C)} H_{n-1}(BC; E(\Gamma/1))) \to \cdots.
\]

This result is obtained by showing the spectral sequence from $[6]$ collapses at $E^2$. The proposition in $[1]$ is stated for the algebraic $K$-theory functor $K$, but holds for any $E$. The reason why cocompact Fuchsian groups are so well-behaved is due to the structure of the lattice of finite subgroups: if $H$ is a non-trivial finite subgroup, then $H$ is contained in a unique maximal finite subgroup $M$, the normalizer $N_M(H)$ equals $M$, and the set of finite subgroups containing $H$ is totally ordered.

When $E$ is a spectrum, and $E_c : \text{Or}(\Gamma, \mathcal{F}\text{in}) \to \text{SPECTRA}$ is the constant functor $\Gamma/H \to E$, the following simplification to Proposition 2 can be made.

Corollary 3. Let $\Gamma$ be a cocompact Fuchsian group with signature $(g; \nu_1, \nu_2, \ldots, \nu_r)$, $E$ be a spectrum, and $X_g$ be the closed orientable surface of genus $g$. Then
\[
\cdots \to \oplus_{(C)} H_n(BC; E) \to (\oplus_{(C)} \pi_n(E)) \oplus H_n(B\Gamma; E) \to H_n(X_g; E) \to \cdots
\]
and
\[
\cdots \to \oplus_{(C)} H_n(BC; E) \to \tilde{H}_n(B\Gamma; E) \to \tilde{H}_n(X_g; E) \to \cdots
\]
are exact.

Proof. By Proposition 2 it suffices to identify $\pi_n(\text{hocolim}_{\text{Or}(\Gamma, \mathcal{F}\text{in})(E_c)})$ with $H_n(X_g; E)$. Let $E_{\mathcal{F}\text{in}1}\Gamma$ be the “universal $\Gamma$-space with finite isotropy”, i.e. a $\Gamma$-complex such that the fixed set $(E_{\mathcal{F}\text{in}1}\Gamma)^H$ is contractible if $H$ is a finite subgroup of $\Gamma$ and empty if $H$ is not finite (see $[5]$, sections 3 and 7). By definition of the homotopy colimit (see $[5]$ sections 3 and 7), $\pi_n(\text{hocolim}_{\text{Or}(\Gamma, \mathcal{F}\text{in})(E_c)}) \cong H_n(E_{\mathcal{F}\text{in}1}\Gamma/\Gamma; E)$ for any constant $\text{Or}(\Gamma, \mathcal{F}\text{in})$-spectrum $E_c$. A cocompact Fuchsian group acts with finite isotropy on the hyperbolic plane $\mathbb{H}^2$ with quotient $X_g$, and we can take $\mathbb{H}^2$ as a model for $E_{\mathcal{F}\text{in}1}\Gamma$.

Proposition 4. Let $\Gamma$ be a cocompact Fuchsian group with signature $(g; \nu_1, \nu_2, \ldots, \nu_r)$ and $X_g$ be the closed orientable surface of genus $g$. There is a commutative diagram with exact rows
\[
\begin{array}{cccccc}
\tilde{KO}_{n+1}(X_g) & \longrightarrow & \oplus_{(C)} \tilde{KO}_n(BC) & \longrightarrow & \tilde{KO}_n(B\Gamma) & \longrightarrow & \tilde{KO}_n(X_g) \\
\downarrow \text{Id} & & \downarrow A & & \downarrow A & & \downarrow \text{Id} \\
\tilde{KO}_{n+1}(X_g) & \longrightarrow & \oplus_{(C)} \tilde{KO}_n(C^*G) & \longrightarrow & \tilde{KO}_n(C^*\Gamma) & \longrightarrow & \tilde{KO}_n(X_g).
\end{array}
\]

Proof. In $[11]$, Hambleton-Pedersen identify the Baum-Connes map with the Davis-Lück assembly map $[2]$ \[\pi_n \text{ hocolim}_{\text{Or}(\Gamma, \mathcal{F}\text{in})} \text{KO}_\text{top} \to \tilde{KO}_n(C^*G).\] Kasparov $[13]$, p. 284] proved that Baum-Connes map is an isomorphism for subgroups of $SO(n,1)$, such as $\Gamma$. Thus we can (and will) replace $\tilde{KO}_n(C^*\Gamma)$ by $\pi_n \text{ hocolim}_{\text{Or}(\Gamma, \mathcal{F}\text{in})} \text{KO}_\text{top}$ in the proof of this proposition.
Underlying Proposition 2 is an “excision” isomorphism,

\[ \pi_*(\vee(C)BC_+ \land \text{KO} \to B\Gamma_+ \land \text{KO}) \xrightarrow{\sim} \pi_*(\vee(C)E(\Gamma/C) \to \hocolim E), \]

defined for every functor \( E : \text{Or}(\Gamma, \mathcal{F}\text{in}) \to \text{SPECTRA} \). Now notice that that for \( H \in \mathcal{F}\text{in} \), there is a morphism in \text{GROUPOIDS}\text{proper} \( \text{KO}_{\text{top}} \to \text{KO}_c \),

inducing a homotopy equivalence \( \text{KO}_{\text{top}}(\Gamma/1) \to \text{KO}_c(\Gamma/1) = \text{KO} \).

Proposition 4 now follows from a diagram chase. Indeed, consider the following diagram.

\[ \pi_*(\vee(C)\text{KO}(C \land C) \to \text{KO}(C_+ \Gamma)) \longrightarrow \pi_*(\text{KO} \to X_{g+} \land \text{KO}) \]

The top row is the excision isomorphism coming from \( \text{KO}_c \) and the left column is the excision isomorphism coming from \( \text{KO}_{\text{top}} \). Commutativity of the diagram comes from the natural transformation \( \text{KO}_{\text{top}} \to \text{KO}_c \). The horizontal isomorphisms give Mayer-Vietoris exact sequences and the commutativity of the square gives a map between the two Mayer-Vietoris sequences. \( \square \)

**Proof of Main Theorem.** Let \( \text{ko} \) be the spectrum for the connective cover of \( \text{KO} \). Since there is a natural transformation \( p : \text{ko}_c \to \text{KO}_c \) of \( \text{Or}(\Gamma, \mathcal{F}\text{in})\)-\text{SPECTRA}, Corollary 3 and Proposition 4 give a commutative diagram with exact rows

\[ \tilde{\text{ko}}_{n+1}(X_g) \longrightarrow \oplus(C)\tilde{\text{ko}}_n(BC) \longrightarrow \tilde{\text{ko}}_n(B\Gamma) \longrightarrow \tilde{\text{ko}}_n(X_g) \]

\[ \downarrow p \] \[ \downarrow A_0p \] \[ \downarrow A_0p \] \[ \downarrow p \]

\[ \tilde{\text{KO}}_{n+1}(X_g) \longrightarrow \oplus(C)\tilde{\text{KO}}_n(C_+ \Gamma) \longrightarrow \tilde{\text{KO}}_n(X_g). \]

Now \( \Sigma X_g \simeq (\vee_{2g} S^2) \lor S^3 \), so

\[ \tilde{\text{ko}}_n(X_g) \cong ko_{n-1}(*)^{2g} \oplus ko_{n-2}(*), \]

\[ \tilde{\text{KO}}_n(X_g) \cong KO_{n-1}(*)^{2g} \oplus KO_{n-2}(*), \]

and hence \( p : \tilde{\text{ko}}_n(X_g) \to \tilde{\text{KO}}_n(X_g) \) is an isomorphism for \( n \geq 2 \); an alternative proof uses the Atiyah-Hirzebruch spectral sequence. Suppose now that \( n \geq 5 \) and that

\[ \beta \in \ker(A \circ p : ko_n(B\Gamma) \to \text{KO}_n(C_+ \Gamma)) \cong \ker(A \circ p : \tilde{\text{ko}}_n(B\Gamma) \to \tilde{\text{KO}}_n(C_+ \Gamma)). \]

Then using the commutative diagram and the fact that the \( p \)'s are isomorphisms, one finds an element

\[ \gamma \in \ker(A \circ p : \oplus(C)ko_n(BC) \to \oplus(C)\text{KO}_n(C_+ \Gamma)) \]

which maps to \( \beta \). In 3, Botvinnik-Gilkey-Stolz show a strong version of the GLR conjecture for finite cyclic groups, namely that \( ko^+_n(BC) = \ker(A \circ p : ko_n(BC) \to \)
Thus $\gamma \in \bigoplus (C^*_r C)$, and hence its image $\beta$ lies in $ko^+_n(B\Gamma)$. Thus the strong version of the GLR conjecture for $\Gamma$ is true, namely that

$$ko^+_n(B\Gamma) = \ker(A \circ p : ko_n(B\Gamma) \to KO_n(C^*_r \Gamma)).$$

Hence, by Theorem 2 our main theorem is proved. \[\square\]

**Remark 5.** In fact, [3] shows that $ko^+_n(BC)$ is generated by lens spaces and simply-connected spaces, and our proof shows that same is true for $ko^+_n(B\Gamma)$.

**Remark 6.** Fuchsian groups have almost periodic cohomology, i.e. $H^m(\Gamma) \cong H^{m+2}(\Gamma)$ provided $m > 2$. Thus our main result is not too surprising in view of [3]: the $K$-theory terms arising from $X_g$ in a sense measures the failure of $H^*(\Gamma)$ to be periodic.

**Acknowledgments.** We thank Diarmuid Crowley and Mark Johnson for valuable discussions, and Stephan Stolz for suggesting that we go ahead and do the case of even torsion. The first author acknowledges support of the NSF. The second author acknowledges the support of an NSF-AWM Travel Grant and thanks the mathematics departments of The University of Chicago and Indiana University for their hospitality while work on this paper was being done.

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