NK_0 AND NK_1 OF THE GROUPS C_4 AND D_4

ADDENDUM TO "LOWER ALGEBRAIC K-THEORY OF HYPERBOLIC 3-SIMPLEX REFLECTION GROUPS."

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Abstract. In this addendum we explicitly compute the Bass Nil-groups $NK_i(\mathbb{Z}[C_4])$ for $i = 0, 1$ and $NK_0(\mathbb{Z}[D_4])$. We also show that $NK_1(\mathbb{Z}[D_4])$ is not trivial. Here C_4 denotes the cyclic group of order 4 and D_4 is the dihedral group of order 8.

In [LO], Lafont and Ortiz computed the lower algebraic K-theory of the integral group ring of all 32 hyperbolic 3-simplex reflection groups (see [LO, Tables 6–7]). For 25 of these integral group rings, their computation was completely explicit. For the remaining 7 examples, the expression for some of the K-groups involved the Bass Nil-groups NK_0 and NK_1 associated to D_4 (the dihedral group of order 8).

In [L05], Lück computed the lower algebraic K-theory of the integral group ring of the semi-direct product of the three-dimensional discrete Heisenberg group by C_4 (the cyclic group of order 4). These computations involved the Bass Nil-groups NK_0 and NK_1 associated to C_4 (see [L05, Corollary 3.9]).

In this addendum we compute the Bass Nil-groups

$$NK_n(\mathbb{Z}G) = \ker\{K_n(\mathbb{Z}G[x]) \xrightarrow{x\mapsto 0} K_n(\mathbb{Z}G)\},$$

where G is D_2, C_4 or D_4, and $n = 0, 1$. We will use these calculations to complement the calculations of [L05] and [LO] in 1.5 and 2.9 below.

Our calculation will keep track of the additional structure on the groups $NK_n(A)$ given by the Verschiebung and Frobenius operators, V_m and F_m, as well as the continuous module structure over the ring $W(\mathbb{Z})$ of big Witt vectors; the additive group of $W(\mathbb{Z})$ is the abelian group $(1 + x\mathbb{Z}[[x]])^\times$. (See [We80] for more details.) In fact, it is a module over the slightly larger Cartier algebra consisting of row-and-column finite sums $\sum V_m[a_{mn}]F_n$, where V_m and F_m are the Verschiebung and Frobenius operators, and the $[a]$ are the homotheties operators for $a \in \mathbb{Z}$; see [DW93] as well as Remarks 1.2.1 and 2.4 below. Some of the identities satisfied by these operators include: $V_mV_n = V_{mn}$, $F_mF_n = F_{mn}$, $F_mV_m = m$, $[a]V_m = V_m[a^m]$ and $F_m[a] = [a^m]F_m$.

It is convenient to write V for the continuous $W(\mathbb{F}_2)$-module $x\mathbb{F}_2[x]$, which, as an abelian group, is just a countable direct sum of copies of $\mathbb{F}_2 = \mathbb{Z}/2$ on generators x^i, $i > 0$. The module structure on V is determined by: $V_m(x^n) = x^{mn}$; $[a]x^n = a^nx^n$; $F_m(x^n) = 0$ if $(m, n) = 1$ $(m > 1)$ and $F_d(x^n) = d\,x^{n/d}$ when $d \mid n$.

1. The groups C_2, D_2 and C_4

For the cyclic group $C_2 = \langle\sigma\rangle$ of order two, consider the Rim square:

(1)
$$\begin{array}{ccc} \mathbb{Z}[C_2] & \xrightarrow{\sigma\mapsto +1} & \mathbb{Z} \\ {\scriptstyle \sigma\mapsto -1}\downarrow & & \downarrow{\scriptstyle q} \\ \mathbb{Z} & \xrightarrow{q} & \mathbb{F}_2 \end{array} \quad \text{or equivalently,} \quad \begin{array}{ccc} \mathbb{Z}[C_2] & \xrightarrow{\sigma\mapsto(1,-1)} & \mathbb{Z}\times\mathbb{Z} \\ \downarrow & & \downarrow{\scriptstyle q\times q} \\ \mathbb{F}_2 & \xrightarrow{\Delta} & \mathbb{F}_2\times\mathbb{F}_2 \end{array}$$

from which we immediately get $NK_0(\mathbb{Z}[C_2]) = NK_1(\mathbb{Z}[C_2]) = 0$ as in [Bas68, XII.10.6] and [Mi71, 6.4]. From Guin-Loday-Keune [GL80][Keu81], the double relative group $NK_2(\mathbb{Z}[C_2], \sigma+1, \sigma-1)$ is isomorphic to V, with the Dennis-Stein symbol $\langle x^n(\sigma-1), \sigma+1\rangle$ corresponding to $x^n \in V$. We also have a diagram:

$$\begin{array}{ccccccc} & & NK_2(\mathbb{Z}[C_2],\sigma+1,\sigma-1)\cong V & & & & \\ & & \downarrow\cong & & & & \\ 0 = NK_3(\mathbb{Z}) & \longrightarrow & NK_2(\mathbb{Z}[C_2],\sigma+1) & \xrightarrow{\cong} & NK_2(\mathbb{Z}[C_2]) & \longrightarrow & NK_2(\mathbb{Z}) = 0 \\ & & \downarrow & & \downarrow & & \\ & & 0 = NK_2(\mathbb{Z},2) & \longrightarrow & NK_2(\mathbb{Z}) = 0. & & \end{array}$$

Thus we obtain:

Theorem 1.1. *$NK_2(\mathbb{Z}[C_2]) \cong V$ with $\langle x^n(\sigma-1), \sigma+1\rangle$ corresponding to $x^n \in V$.*

We now turn to the group $D_2 = C_2 \times C_2$. First we need a calculation. Let $\Phi(V)$ denote the subgroup (and Cartier submodule) $x^2\mathbb{F}_2[x^2]$ of V, and write Ω_R for the Kähler differentials of R, so that $\Omega_{\mathbb{F}_2[x]} \cong \mathbb{F}_2[x]dx$. By abuse, we will write $\mathbb{F}_2[\varepsilon]$ for the 2-dimensional algebra $\mathbb{F}_2[\varepsilon]/(\varepsilon^2)$.

Lemma 1.2. *The map $q : \mathbb{Z}[C_2] \to \mathbb{F}_2[C_2] \cong \mathbb{F}_2[\varepsilon]$ in (1) induces an exact sequence*

$$0 \to \Phi(V) \to NK_2(\mathbb{Z}[C_2]) \xrightarrow{q} NK_2(\mathbb{F}_2[\varepsilon]) \xrightarrow{D} \Omega_{\mathbb{F}_2[x]} \to 0.$$

Proof. Van der Kallen computed $NK_2(\mathbb{F}_2[\varepsilon])$ in [vdK71, Ex. 3]: there is a split short exact sequence

(2)
$$0 \to V/\Phi(V) \xrightarrow{F} NK_2(\mathbb{F}_2[\varepsilon]) \xrightarrow{D} \Omega_{\mathbb{F}_2[x]} \to 0,$$

where $F(x^n) = \langle x^n\varepsilon, \varepsilon\rangle$ and $D(\langle f\varepsilon, g + g'\varepsilon\rangle) = f\,dg$. The map $NK_2(\mathbb{Z}[C_2]) \xrightarrow{q} NK_2(\mathbb{F}_2[\varepsilon])$ sends $\langle x^n(\sigma+1), \sigma-1\rangle$ to $F(x^n) = \langle x^n\varepsilon, \varepsilon\rangle$. By Theorem 1.1 and (2), this map has kernel $\Phi(V)$ and image $F(V/\Phi(V))$. □

Remark 1.2.1. Although $\Omega_{\mathbb{F}_2[x]}$ is isomorphic to V as an abelian group, it has a different $W(\mathbb{F}_2)$-module structure. This is determined by the formulas in $\Omega_{\mathbb{F}_2[x]}$:

$$V_m(x^{n-1}\,dx) = mx^{mn-1}dx, \quad F_m(x^{n-1}dx) = \begin{cases} x^{n/m-1}dx & \text{if } m \mid n \\ 0 & \text{else.} \end{cases}$$

Grunewald has pointed out that since $\Omega_{\mathbb{F}_2[x]}$ is not finitely generated as a module over the $\mathbb{F}_2$-Cartier algebra (of row-and-column finite sums $\sum V_m[a_{mn}]F_n$), or over the subalgebra $W(\mathbb{F}_2)$), neither are $NK_2(\mathbb{F}_2[\varepsilon])$ or (by 1.3 below) $NK_1(\mathbb{Z}[D_2])$.

Theorem 1.3. *For $D_2 = C_2 \times C_2$, $NK_0(\mathbb{Z}[D_2]) \cong V$, $NK_1(\mathbb{Z}[D_2]) \cong \Omega_{\mathbb{F}_2[x]}$ and the image of the map $NK_2(\mathbb{Z}[D_2]) \to NK_2(\mathbb{Z}[C_2])^2 \cong V^2$ is $\Phi(V) \times V$.*

Proof. We tensor (1) with $\mathbb{Z}[C_2]$. Since $\mathbb{F}_2[C_2] \cong \mathbb{F}_2[\varepsilon]$, $\varepsilon^2 = 0$, and $NK_1(\mathbb{F}_2[C_2]) \cong (1 + x\varepsilon\mathbb{F}_2[x])^\times \cong V$, then the Mayer-Vietoris sequence in [Mi71, Theorem 6.4] for the NK-functor,

$$\begin{aligned} &NK_2(\mathbb{Z}[D_2]) \to (NK_2(\mathbb{Z}[C_2]))^2 \xrightarrow{q\times q} NK_2(\mathbb{F}_2[\varepsilon]) \to NK_1(\mathbb{Z}[D_2]) \\ &\to (NK_1(\mathbb{Z}[C_2])^2 \to NK_1(\mathbb{F}_2[\varepsilon]) \xrightarrow{\cong} NK_0(\mathbb{Z}[D_2]) \to NK_0(\mathbb{Z}[C_2]), \end{aligned} \tag{3}$$

quickly gives $NK_0(\mathbb{Z}[D_2]) \cong NK_1(\mathbb{F}_2[\varepsilon]) \cong V$. By Lemma 1.2, the initial portion of (3) yields the calculation of $NK_1(\mathbb{Z}[D_2])$ and the asserted surjection $NK_2(\mathbb{Z}[D_2]) \twoheadrightarrow \Phi(V) \times V$. □

Remark. The kernel K of the map $NK_2(\mathbb{Z}[D_2]) \to V^2$ in Theorem 1.3 has a subgroup generated by the double relative group $NK_2(\mathbb{Z}[D_2], \sigma_1 + 1, \sigma_1 - 1)$, which is isomorphic to $\mathbb{F}_2[\varepsilon] \otimes V$ on the symbols $\langle x^n(a + b\sigma_2)(\sigma_1 + 1), \sigma_2 - 1\rangle$, where σ_1, σ_2 are the generators of $D_2 = C_2 \times C_2$. The quotient of K by this subgroup is generated by the image of $NK_3(\mathbb{F}_2[\varepsilon])$, a group which I do not know.

The analysis for the cyclic group C_4 of order 4 on generator σ is similar, using the Rim square

$$\begin{array}{ccc} \mathbb{Z}[C_4] & \xrightarrow{\sigma\mapsto i} & \mathbb{Z}[i] \\ {\scriptstyle \sigma^2\mapsto 1}\downarrow & & \downarrow{\scriptstyle i\mapsto 1+\varepsilon} \\ \mathbb{Z}[C_2] & \xrightarrow{q} & \mathbb{F}_2[\varepsilon] \end{array} \quad . \tag{4}$$

Theorem 1.4. *$NK_1(\mathbb{Z}[C_4]) \cong \Omega_{F_2[x]}$ and $NK_0(\mathbb{Z}[C_4]) \cong V$.*

Proof. Since $\mathbb{Z}[i]$ is a regular ring, the Mayer-Vietoris sequence for (4) reduces to:

$$\begin{aligned} &NK_2(\mathbb{Z}[C_4]) \xrightarrow{p_2} NK_2(\mathbb{Z}[C_2]) \xrightarrow{q} NK_2(\mathbb{F}_2[\varepsilon]) \to NK_1(\mathbb{Z}[C_4]) \\ &\to NK_1(\mathbb{Z}[C_2]) \to NK_1(\mathbb{F}_2[\varepsilon]) \xrightarrow{\cong} NK_0(\mathbb{Z}[C_4]) \to NK_0(\mathbb{Z}[C_2]). \end{aligned}$$

The isomorphism marked in this sequence follows from Theorem 1.1. By Lemma 1.2, the image of the first map p_2 is $\Phi(V)$ and the cokernel of the map q is $\Omega_{\mathbb{F}_2[\varepsilon]}$. □

Remark. The proof provides a surjection $NK_2(\mathbb{Z}[C_4]) \xrightarrow{p_2} \Phi(V)$. The kernel of p_2 contains the image E of the double relative group $NK_2(\mathbb{Z}[C_4], \sigma^2 + 1, \sigma^2 - 1)$, which is isomorphic to $\mathbb{F}_2[\varepsilon] \otimes V$ on symbols $\langle \sigma^2 + 1, x^n(\sigma^2 - 1)\rangle$. The quotient $\ker(p_2)/E$ is generated by the image of $NK_3(\mathbb{F}_2[\varepsilon])$, which I do not know.

Here is an application of this calculation. Let Hei denote the *three-dimensional discrete Heisenberg group*, which is the subgroup of $GL(3, \mathbb{Z})$ consisting of upper triangular integral matrices with ones along the diagonal. Consider the action of the cyclic group C_4 given by:

$$\begin{pmatrix} 1 & x & y \\ 0 & 1 & z \\ 0 & 0 & 1 \end{pmatrix} \mapsto \begin{pmatrix} 1 & -z & y - xz \\ 0 & 1 & x \\ 0 & 0 & 1 \end{pmatrix}.$$

Combining Theorem 1.4 with [L05, 3.9], the lower K-theory of the group $\mathrm{Hei} \rtimes C_4$ is given in the following proposition.

Proposition 1.5. *We have:* $Wh_n(\mathrm{Hei} \rtimes C_4) = \begin{cases} \bigoplus_\infty \mathbb{Z}/2 & n = 0, 1; \\ 0 & n \leq -1. \end{cases}$

2. The dihedral group D_4

Before moving on to the group ring of D_4, we need some facts about the double relative groups $K_1(A,B,I)$ when $A\to B$ is an injection. These groups were described in [GW83, 0.2] as:

(5) $K_1(A,B,I)\cong(B/A)\otimes(I/I^2)/\{b\otimes cz+c\otimes zb-bc\otimes z\},\quad(b,c\in B,z\in I).$

Moreover, by [GW83, 3.12 and 4.1], the map $K_1(A,B,I)\to K_1(A,I)$ sends the class of $b\otimes z$ to the class of the matrix $\left(\begin{smallmatrix}1-zb & z\\ -bzb & 1+bz\end{smallmatrix}\right)$.

Lemma 2.1. *Suppose that $A\to B$ is a ring homomorphism mapping an ideal I of A isomorphically onto an ideal of B. Then the double relative group satisfies*

$$K_1(A[x],B[x],I[x])\cong K_1(A,B,I)\otimes\mathbb{Z}[x],\ \text{and}\ NK_1(A,B,I)\cong K_1(A,B,I)\otimes x\mathbb{Z}[x].$$

Proof. Because x is central in $B[x]$, the formulas are immediate from (5). □

We will be specifically interested in the twisted group ring $A=\mathbb{Z}[i]\rtimes C_2$, where $C_2=\langle\tau\rangle$ acts on $\mathbb{Z}[i]$ by $\tau i\tau^{-1}=-i$. It injects into the matrix ring $B=M_2(\mathbb{Z})$ by the map $\phi:A\to B$ defined by $\phi(i)=\left(\begin{smallmatrix}0&1\\-1&0\end{smallmatrix}\right)$ and $\phi(\tau)=\left(\begin{smallmatrix}1&0\\0&-1\end{smallmatrix}\right)$. The ideal $I=(2,1+\tau)A$ maps isomorphically to $2B$, and $A/I\cong\mathbb{F}_2[\varepsilon_1]$, where $\varepsilon_1=1+i$ and $\varepsilon_1^2=0$. Hence we have the following cartesian square:

(6)
$$\begin{array}{ccc} A & \xrightarrow{\ \phi\ } & M_2(\mathbb{Z})\\ {\scriptstyle \mathrm{mod}\, I}\downarrow & & \downarrow{\scriptstyle \mathrm{mod}\, 2B}\\ \mathbb{F}_2[\varepsilon_1] & \longrightarrow & M_2(\mathbb{F}_2). \end{array}$$

To calculate $NK_1(A)$, we use the following double relative calculation.

Lemma 2.2. *The double relative group $K_1(A,B,2B)$ of (6) is isomorphic to $\mathbb{F}_2$, and $NK_1(A,B,2B)\cong V$. The map $V\cong NK_1(A,B,2B)\to NK_1(A)$ sends $x^n\in V$ to the class of the unit $1+x^ni(1+\tau)$ of $A[x]$.*

Proof. Since $\dim(B/A)=2$ and $\dim(I/I^2)=4$, the group $(B/A)\otimes(I/I^2)$ has 8 generators and 64 relations; a basis of B/A is $\{e_{11},e_{12}\}$ and the $2e_{ij}$ span I/I^2. By inspection of the relations in (5) we see that the map $B/I\otimes I/I^2\to\mathbb{F}_2$ sending $e_{ij}\otimes 2e_{kl}$ to $\delta_{il}+\delta_{jk}$ sends $A/I\otimes I/I^2$ and all the relations in (5) to zero, and sends $e_{11}\otimes 2e_{12}$ to 1. Thus it induces a surjection $K_1(A,B,I)\to\mathbb{F}_2$. We claim that this is an isomorphism.

The relations for $(b,c,z)=(e_{11},e_{11},2e_{11})$, $(e_{11},e_{11},2e_{22})$, $(e_{11},e_{12},2e_{12})$ and $(e_{11},e_{21},2e_{21})$ in (5) yields the relations:

$$0=e_{11}\otimes 2e_{11}=e_{11}\otimes 2e_{22}=e_{12}\otimes 2e_{12}=e_{21}\otimes 2e_{21}.$$

The relations for $(e_{12},e_{11},2e_{11})$, $(b,c,z)=(e_{11},e_{21},2e_{11})$ and $(e_{12},e_{12},2e_{21})$ in (5) yields the relations:

$$0=e_{11}\otimes 2e_{12}-e_{12}\otimes 2e_{11}=e_{21}\otimes 2e_{11}-e_{11}\otimes 2e_{21}=e_{12}\otimes 2e_{22}-e_{12}\otimes 2e_{11}.$$

This verifies the claim, proving that $K_1(A,B,2B)\cong\mathbb{F}_2$.

Finally, the map $NK_1(A,B,2B)\to NK_1(A,I)$ sends the class of $x^ne_{11}\otimes 2e_{12}$ to the class of the matrix $\left(\begin{smallmatrix}1-2x^ne_{12}e_{11} & 2x^ne_{12}\\ -x^{2n}e_{11}e_{12}e_{11} & 1+2x^ne_{11}e_{12}\end{smallmatrix}\right)=\left(\begin{smallmatrix}1 & x^ni(1+\tau)\\ 0 & 1+x^ni(1+\tau)\end{smallmatrix}\right)$, which is the class of $1+x^ni(1+\tau)$ in $NK_1(A)$. □

Remark. The elements $u = i + \tau$ and $v = i(1+\tau)$ of A satisfy $u^2 = v^2 = 0$, and are distinct in $A/2A = \mathbb{F}_2[i,\tau]$. Hence the units $(1+x^m u)(1+x^n v)$ of $A[x]$ generate a subgroup of $NK_1(A)$ isomorphic to V^2, which injects into $NK_1(\mathbb{F}_2[i,\tau]) \cong V^3$. (Since $\mathbb{F}_2[i,\tau] = \mathbb{F}_2[u,v]/(u^2,v^2)$, the other copy of V in $NK_1(\mathbb{F}_2[i,\tau])$ is the subgroup generated by all $(1+x^n uv)$.)

Proposition 2.3. *$NK_0(A) = 0$ and $NK_1(A) \cong V^2$ on the units $(1+x^m u)(1+x^n v)$.*

The map $A \to \mathbb{F}_2[i,\tau] \cong \mathbb{F}_2[\varepsilon_1,\varepsilon_2]$ and the map $\Omega_{\mathbb{F}_2[x]} \xrightarrow{\delta} NK_2(\mathbb{F}_2[\varepsilon_1,\varepsilon_2])$ sending x^n to $\langle x^{n-1}\varepsilon_1\varepsilon_2, x\rangle$ induce a surjection $NK_2(A) \times \Omega_{\mathbb{F}_2[x]} \to NK_2(\mathbb{F}_2[\varepsilon_1,\varepsilon_2])$.

Proof. Consider the Mayer-Vietoris sequence of the square (6). Since $B = M_2(\mathbb{Z})$ and $B/I = M_2(\mathbb{F}_2)$ are regular rings, $NK_n(B) = NK_n(B/I) = 0$ and hence $NK_n(B,I) = 0$ for all n. We immediately get that $NK_n(A,B,I) \cong NK_n(A,I)$, that the Mayer-Vietoris sequence reduces to $NK_0(A) \cong NK_0(A/I) = 0$, and that there is an exact sequence:

$$NK_2(A) \to NK_2(\mathbb{F}_2[\varepsilon_1]) \to NK_1(A,B,I) \to NK_1(A) \to NK_1(\mathbb{F}_2[\varepsilon_1]) \to 0.$$

By Lemma 2.2 and the remark preceding it, this yields the calculation of $NK_1(A)$.

Now $\pi : A \to \mathbb{F}_2[\varepsilon_1,\varepsilon_2]$ satisfies $\pi(u) = \varepsilon_1+\varepsilon_2$, $\pi(v) = \varepsilon_1+\varepsilon_1\varepsilon_2$ and $\pi(uv) = \varepsilon_1\varepsilon_2$, so we may write $\mathbb{F}_2[\varepsilon_1,\varepsilon_2] \cong \mathbb{F}_2[\bar{u},\bar{v}]/(\bar{u}^2,\bar{v}^2)$. By [vdK71], the group $NK_2(\mathbb{F}_2[\bar{u},\bar{v}])$ is isomorphic to the direct sum of $NK_2(\mathbb{F}_2[\bar{u}])$, $NK_2(\mathbb{F}_2[\bar{v}])$ and a group with the following generators:

$$\langle x^n\bar{u},\bar{v}\rangle, \langle x^n\bar{u}\bar{v},\bar{u}\rangle, \langle x^n\bar{u}\bar{v},\bar{v}\rangle \text{ and } \langle x^{n-1}\bar{u}\bar{v},x\rangle.$$

Since $u^2 = v^2 = 0$ in A, all these symbols lift to Dennis-Stein symbols in $NK_2(A)$ except possibly the symbols $\langle x^{n-1}\bar{u}\bar{v},x\rangle$. But these symbols are hit by the image of $\Omega_{\mathbb{F}_2[x]}$ under δ. □

Remark. $\delta : \Omega_{\mathbb{F}_2[x]} \to NK_2(\mathbb{F}_2[\varepsilon_1,\varepsilon_2])$ is a homomorphism by the Dennis-Stein identity $\langle f,x\rangle\langle g,x\rangle = \langle f+g-fgx, x\rangle$ with $fg = 0$; see [GL80, p. 184]. It is a morphism of $\mathbb{F}_2$-Cartier modules since $V_m\langle x^{n-1}\varepsilon_1\varepsilon_2,x\rangle = m\langle x^{mn-1}\varepsilon_1\varepsilon_2,x\rangle = \delta(V_m(x^n))$ and (by [St80, 2.1])

$$F_m\langle x^{n-1}\varepsilon_1\varepsilon_2,x\rangle = \begin{cases} \langle x^{n/m-1}\varepsilon_1\varepsilon_2,x\rangle, & m \mid n \\ r\langle x^{n-1}(\varepsilon_1\varepsilon_2)^m,x\rangle - s\langle x^n(\varepsilon_1\varepsilon_2)^{m-1},\varepsilon_1\varepsilon_2\rangle = 0, & rm+sn = 1. \end{cases}$$

Our analysis of D_4 will involve the units of the ring $\mathbb{Z}/4[x][C_2]$.

Example 2.4. *Consider the modular group ring $B = \mathbb{Z}/4[C_2] = \mathbb{Z}/4[e]/(e^2-2e)$, with $e = 1-\tau$. The ideals $2eB$ of B and $eB/2eB$ of $B/2eB$ are isomorphic to $\mathbb{F}_2$, so both $NK_1(B,2e)$ and $NK_1(B/2e,e)$ are isomorphic to V and the group $NK_1(B,e)$, identified with the abelian group $(1+xeB[x])^\times$ is a nontrivial extension:*

$$0 \to V \to NK_1(B,e) \to V \to 0.$$

As an abelian group, $NK_1(B,e)$ is the direct sum of a countably infinite free $\mathbb{Z}/4$-module on the $(1+ex^m)$ $(m = 1,2,\dots)$ and a countably infinite free $\mathbb{Z}/2$-module on the $(1+2ex^{2i-1})$ $(i = 1,2,\dots)$. As a module over the $\mathbb{Z}/4$-Cartier algebra (generated by the operators V_m, F_m and homothety $[2]$), $NK_1(B,e)$ is cyclic on generator $u = 1+ex$; $V_m(u) = 1+ex^m$ and $V_m[2](u) = 1+2ex^m$.

Finally, we are in position to analyze $NK_0(\mathbb{Z}[D_4])$. The sharp exponent 4 for $NK_0(\mathbb{Z}[D_4])$ in Theorem 2.5 is a slight improvement on the bound in [CP02]. It is convenient to write D_4 as the semidirect product of C_4 (on σ) with the cyclic group $C_2 = \{1, \tau\}$, with relation $\tau\sigma\tau = \sigma^{-1}$.

Theorem 2.5. *The group $NK_0(\mathbb{Z}[D_4])$ is isomorphic to the cyclic Cartier module $NK_1(\mathbb{Z}/4[C_2], 1-\tau)$, described in Example 2.4. As a group, it is the direct sum of a countably infinite free $\mathbb{Z}/4$-module and a countably infinite free $\mathbb{Z}/2$-module.*

Proof. We can map $\mathbb{Z}[D_4]$ to the twisted ring $A = \mathbb{Z}[i] \rtimes C_2$ occurring in (6) above, sending σ to i. Combining this with the natural surjection onto the subring $\mathbb{Z}[D_2]$ of $\mathbb{Z}[C_2] \times \mathbb{Z}[C_2]$, we get a ring map $\mathbb{Z}[D_4] \to A \times \mathbb{Z}[C_2] \times \mathbb{Z}[C_2]$. The ideal $I = (4, 2-2\sigma, \sigma^2-1)\mathbb{Z}[D_4]$ has $B_0 = \mathbb{Z}[D_4]/I = \mathbb{Z}/4[D_2]/(2-2\sigma)$, and is isomorphic to the ideal $2A \times (4) \times (4)$ of $A \times \mathbb{Z}[C_2] \times \mathbb{Z}[C_2]$. Consider the following cartesian square:

$$\begin{array}{ccc} \mathbb{Z}[D_4] & \xrightarrow[\tau\mapsto(\tau,\tau,\tau)]{\sigma\mapsto(i,1,-1)} & A \times \mathbb{Z}[C_2] \times \mathbb{Z}[C_2] \\ \downarrow & & \downarrow{\scriptstyle \pi} \\ B_0 = \mathbb{Z}/4[D_2]/(2-2\sigma) & \xrightarrow{q=(q_0,q_+,q_-)} & \mathbb{F}_2[D_2] \times B \times B. \end{array} \tag{7}$$

The kernel of the split surjection $q_+ : B_0 \to B = \mathbb{Z}/4[C_2]$ is the 2-dimensional ideal $J = (1-\sigma)B_0$. This implies that $NK_1(B_0) = NK_1(B) \oplus NK_1(B_0, J)$. Because $NK_1(\mathbb{Z}[C_2]) = NK_0(\mathbb{Z}[C_2]) = NK_0(A) = 0$ (by 2.3), the Mayer-Vietoris sequence associated to (7) ends

$$NK_1(A) \times NK_1(B_0, J) \xrightarrow{\eta} NK_1(\mathbb{F}_2[D_2]) \times NK_1(B) \to NK_0(\mathbb{Z}[D_4]) \to 0. \tag{8}$$

The displayed map η is given by the matrix $\left(\begin{smallmatrix}\pi & 0\\ q_0 & q_-\end{smallmatrix}\right)$. It is easy to see that $NK_1(B_0, J)$ is isomorphic to V^2 on the terms $(1+(1-\sigma)x^m)$ and $(1+(1-\sigma)\tau x^n)$. An elementary calculation using the isomorphism $NK_1(A) \cong V^2$ of 2.3 shows that η is an injection, sending the module $NK_1(A) \times NK_1(B_0, J) \cong V^4$ isomorphically onto the subgroup $NK_1(\mathbb{F}_2[D_2]) \times NK_1(\mathbb{Z}/4)$. Since $NK_1(B) = NK_1(\mathbb{Z}/4) \oplus NK_1(B, eB)$, $e = 1-\tau$, it follows that the induced map $NK_1(B, e) \to NK_0(\mathbb{Z}[D_4])$ is an isomorphism. $\square$

To begin the calculation of $NK_1(\mathbb{Z}[D_4])$, we extend the Mayer-Vietoris sequence (8) associated to (7) to the left. This is possible by the following observation: since B_0 maps onto each of the three ring factors on the lower right of (7), the presentation (5) shows that the double relative K_1 obstruction vanishes. Because η is an injection in (8), the continuation of the Mayer-Vietoris sequence yields the exact sequence:

$$(*) \xrightarrow{\left(\begin{smallmatrix}\pi & 0\\ q_0 & q_-\end{smallmatrix}\right)} NK_2(\mathbb{F}_2[D_2]) \times NK_2(B) \to NK_1(\mathbb{Z}[D_4]) \to 0. \tag{9}$$

where $(*)$ denotes $NK_2(A) \times NK_2(\mathbb{Z}[C_2])^2 \times NK_2(B_0, J)$.

Definition 2.6. The map $\cup[x] : NK_0(\mathbb{Z}[D_4]) \to NK_1(\mathbb{Z}[D_4])$ is obtained by composing the isomorphism $NK_1(B, e) \cong NK_0(\mathbb{Z}[D_4])$ of Theorem 2.5 with the canonical map $NK_2(B, e) \to NK_2(B) \to NK_1(\mathbb{Z}[D_4])$ of (9).

Remark. There is also a canonical map $NK_1(B, e) \to NK_2(B, e)$ sending the unit $1 - aex$ to $\langle ae, x\rangle$; the composition with $NK_2(B, e) \subset K_2(B[x, x^{-1}], e)$ is given by $1 - aex \mapsto \{1 - aex, x\}$ (multiplication by the class of x in $K_1(\mathbb{Z}[x, x^{-1}])$).

The analogous maps from $V \cong NK_1(B, 2e)$ and $V \cong NK_1(B/2eB, e)$ to $\Omega_{\mathbb{F}_2[x]} \cong NK_2(B, 2e)$ and $\Omega_{\mathbb{F}_2[x]} \cong NK_2(B/2eB, e)$ are compatible with the divided power map $[d] : V \to \Omega_{\mathbb{F}_2[x]}$ sending x^n to $x^{n-1}\,dx$. Note that $[d]$ is an isomorphism of abelian groups but is not a morphism of $\mathbb{F}_2$-Cartier modules.

Theorem 2.7. *The map $\cup[x] : NK_0(\mathbb{Z}[D_4]) \to NK_1(\mathbb{Z}[D_4])$ in 2.6 is a surjection. Hence the group $NK_1(\mathbb{Z}[D_4])$ has exponent 2 or 4, and there is a commutative diagram whose rows are exact:*

$$\begin{array}{ccccccccc} 0 & \longrightarrow & V & \longrightarrow & NK_0(\mathbb{Z}[D_4]) & \longrightarrow & V & \longrightarrow & 0 \\ & & \cong \downarrow [d] & & \downarrow \cup[x] & & \cong \downarrow [d] & & \\ & & \Omega_{\mathbb{F}_2[x]} & \longrightarrow & NK_1(\mathbb{Z}[D_4]) & \longrightarrow & \Omega_{\mathbb{F}_2[x]} & \longrightarrow & 0. \end{array}$$

Proof. A diagram chase on (9) shows that $NK_1(\mathbb{Z}[D_4])$ is an extension of the cokernel of $NK_2(\mathbb{Z}[C_2]) \times NK_2(B_0, J) \to NK_2(B)$ by a quotient of the cokernel of $NK_2(A) \to NK_2(\mathbb{F}_2[D_2])$. These cokernels are both $\Omega_{\mathbb{F}_2[x]}$, by Proposition 2.3 and Lemma 2.8 below, yielding the bottom row of the theorem. The map $\cup[x]$ sends the element corresponding to $1 - x^n ae \in NK_1(B, e)$ to the element corresponding to $\langle x^{n-1}ae, x\rangle \in NK_2(B, e)$, so the diagram in the theorem commutes by inspection. □

Lemma 2.8. *The cokernel of the map $NK_2(\mathbb{Z}[C_2]) \times NK_2(B_0, J) \to NK_2(B)$ in (9) is $\Omega_{\mathbb{F}_2[x]}$, on symbols $\langle x^{n-1}e, x\rangle$.*

Proof. The kernel of the map $q_- : B_0 \to B$ is the ideal $J' = (1 + \sigma)B_0$. Because $J \cap J' = 0$ in B_0, the double relative group $NK_2(B_0, J, J')$ is isomorphic to $\mathbb{F}_2[C_2][x]$ on symbols $\langle x^m(1+\sigma), (1-\sigma)\rangle$ and $\langle x^m\tau(1+\sigma), (1-\sigma)\rangle$ by [GL80][Keu81]. Since $J \cong 2B$, we have an exact sequence

$$\mathbb{F}_2[C_2][x] \to NK_2(B_0, J) \xrightarrow{q_-} NK_2(B, 2B) \to 0. \tag{10}$$

Combining this with the ideal sequence for $2B \subset B$ shows that the cokernel of $NK_2(B_0, J) \to NK_2(B)$ is $NK_2(B/2B)$. Since $B/2B \cong \mathbb{F}_2[C_2]$, the lemma now follows from Lemma 1.2. □

Inserting the calculations of Theorems 2.5 and 2.7 into Tables 6–7 in [LO], we obtain the following result.

Theorem 2.9. *Let Γ be one of the following hyperbolic 3-simplex reflection groups: $[(3, 4, 3, 6)]$, $[4, 3^{[3]}]$, $[4, 3, 6]$, $[(3^3, 4)]$, $[4, 3, 5]$, $[(3, 4)^{[2]}]$, $[(3, 4, 3, 5)]$. Then the lower algebraic K-theory of the groups Γ is given by the following table:*

Γ	$K_{-1} \neq 0$	$\tilde{K}_0 \neq 0$	$Wh \neq 0$
$[(3,4,3,6)]$	$\mathbb{Z}^3$	$(\mathbb{Z}/4)^2 \oplus Nil_0$	Nil_1
$[4,3^{[3]}]$	$\mathbb{Z}^3$	$(\mathbb{Z}/4)^2 \oplus Nil_0 \oplus \bigoplus_\infty \mathbb{Z}/2$	$Nil_1 \oplus \bigoplus_\infty \mathbb{Z}/2$
$[4,3,6]$	$\mathbb{Z}^4$	$(\mathbb{Z}/4)^2 \oplus Nil_0 \oplus \bigoplus_\infty \mathbb{Z}/2$	$Nil_1 \oplus \bigoplus_\infty \mathbb{Z}/2$
$[(3^3,4)]$	$\mathbb{Z}^2$	$(\mathbb{Z}/4)^2 \oplus Nil_0 \oplus \bigoplus_\infty \mathbb{Z}/2$	$Nil_1 \oplus \bigoplus_\infty \mathbb{Z}/2$
$[4,3,5]$	$\mathbb{Z}^3$	$(\mathbb{Z}/4)^2 \oplus Nil_0 \oplus \bigoplus_\infty \mathbb{Z}/2$	$\mathbb{Z}^3 \oplus Nil_1 \oplus \bigoplus_\infty \mathbb{Z}/2$
$[(3,4)^{[2]}]$	$\mathbb{Z}^4$	$(\mathbb{Z}/4)^4 \oplus Nil_0 \oplus \bigoplus_\infty \mathbb{Z}/2$	$Nil_1 \oplus \bigoplus_\infty \mathbb{Z}/2$
$[(3,4,3,5)]$	$\mathbb{Z}^4$	$(\mathbb{Z}/4)^2 \oplus Nil_0 \oplus \bigoplus_\infty \mathbb{Z}/2$	$\mathbb{Z}^3 \oplus Nil_1 \oplus \bigoplus_\infty \mathbb{Z}/2$

In this table, $Nil_0 = NK_i(\mathbb{Z}[D_4])$ is the direct sum of a countably infinite free $\mathbb{Z}/4$-module and a countably infinite free $\mathbb{Z}/2$-module, and $Nil_1 = NK_1(\mathbb{Z}[D_4])$ is a countably infinite torsion group of exponent 2 or 4.

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