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Author(s)	Kamata, Masayoshi
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Kamata, M.
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THE STRUCTURE OF THE BORDISM GROUP $U_*(BZ_p)$

Dedicated to Professor Keizo Asano on his 60th birthday

MASAYOSHI KAMATA

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In this paper, we determine the additive structure of the complex bordism group $U_*(BZ_p)$, where BZ_p is a classifying space for Z_p , p a odd prime. Conner-Floyd [1] computed the case $p=2$, and solved by a geometric method. Here we use the Mischenko series [4] instead of the geometric method of Conner-Floyd.

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1. The order of the element $[L^{n-1}(p), i]$

We denote by $U_*(X, A)$ and $U^*(X, A)$ the complex bordism group and the complex cobordism group of a CW complex pair (X, A) respectively. Let $L^n(p)$ be a $(2n+1)$ -dimensional lens space defined by a rotation Γ which acts on a $(2n+1)$ -sphere S^{2n+1} in complex coordinate by $\Gamma(z_0, \dots, z_n) = (\rho z_0, \dots, \rho z_n)$ with $\rho = \exp(2\pi i/p)$. BZ_p is a CW complex of which the $(2n+1)$ -skeleton is $L^n(p)$. The cell structure of $L^n(p)$ is given as follows:

$$L^n(p) = s^1 \cup_p e^2 \cup e^3 \cup_p \dots \cup_p e^{2n} \cup e^{2n+1}.$$

Applying the exact sequence of the bordism group to a pair $(L^{n+1}(p), L^n(p))$, it follows immediately that

$$U_k(L^n(p)) \approx U_k(L^{n+1}(p)) \text{ for } k < 2n+1.$$

In this section we study the order of the element

$$[L^{n-1}(p), i] \in U_{2n-1}(L^n(p)) \approx \dots \approx U_{2n-1}(BZ_p),$$

where $i: L^{n-1}(p) \rightarrow L^n(p)$ is the inclusion. In order to determine the order of $[L^{n-1}(p), i]$, we use the duality isomorphism between bordism groups and cobordism groups, and the relation between K -theories and cobordism theories.

Theorem 1.1 (Atiyah-Kultze [3]). *If X is an n -dimensional compact U -manifold, there is an isomorphism $D: U_k(X) \rightarrow U^{n-k}(X)$.*

$D[M^k, f]$ is given as follows. For a large integer r such that $n+r-k$ is even, there is an embedding map $\tilde{f}: M^k \rightarrow S^r X^+ - \{*\}$, which is homotopic to the map $f: M^k \rightarrow X \subset S^r X^+ - \{*\}$, where $*$ denotes the base point. Denote by $N(M^k)$ the normal bundle of $M^k \subset S^r X^+ - \{*\}$, and there is a bundle map φ from $N(M^k)$ to the $(n+r-k)/2$ -dimensional universal complex bundle $EU((n+r-k)/2)$. Then we can construct the map

$$d(f): S^r X^+ \rightarrow T(N(M^k)) \xrightarrow{\phi} MU((n+r-k)/2),$$

where $T(N(M^k))$ and $MU((n+r-k)/2)$ are Thom complexes of $N(M^k)$ and $EU((n+r-k)/2)$ respectively. $D[M^k, f] = [d(f)]$.

The following theorem which connects K -theories with cobordism theories was given by Conner-Floyd [1].

Theorem 1.2 (Conner-Floyd). *If X is a finite connected CW complex, the homomorphism $\rho: \tilde{K}(X) \rightarrow U^2(X)$ which maps $\{\xi^n\} - n$ into the 1-st cobordism Chern class $c_1(\xi^n)$ of ξ^n is the monomorphism of $\tilde{K}(X)$ onto a direct summand of $U^2(X)$.*

Let $\pi: L^n(p) \rightarrow CP^n$ be a canonical projection. If η is a canonical complex line bundle over CP^n , $\tau_c(CP^n) \oplus 1_c = (n+1)\eta$ and $\tau(L^n(p)) \oplus 1 = \pi^*(\tau(CP^n) \oplus 2)$, where $\tau(L^n(p))$ and $\tau(CP^n)$ are tangent bundles over $L^n(p)$ and CP^n respectively, and lower index c denotes a complex vector bundle. Therefore $L^n(p)$ is a U -manifold. Considering homomorphisms D and ρ of Theorems 1.1 and 1.2 for a space $L^n(p)$, we have the following

Proposition 1.3. $D[L^{n-1}(p), i] = \rho(\pi^*\eta - 1_c)$.

Proof. Let ν_c be the normal bundle of CP^{n-1} in CP^n . Since $\tau_c(CP^n)|_{CP^{n-1}} = \tau_c(CP^{n-1}) \oplus \nu_c$,

$$r((\tau_c(CP^n)|_{CP^{n-1}}) \oplus 1_c) = r(\tau_c(CP^{n-1}) \oplus 1_c \oplus \nu_c),$$

where r denotes the real restriction. Moreover,

$$\pi^*r(\tau_c(CP^n) \oplus 1_c)|_{CP^{n-1}} = \pi^*r\{(\tau_c(CP^{n-1}) \oplus 1_c) \oplus \nu_c\},$$

which implies that $\pi^*r\nu_c$ is the normal bundle of $L^{n-1}(p)$ in $L^n(p)$. The total space $E(\tau_c(CP^n))$ of $\tau_c(CP^n)$ can be represented as the set of all pairs $[\tilde{u}, \tilde{v}]$ with $\|\tilde{u}\|=1$, $\tilde{u} \in C^{n+1}$ and $\langle \tilde{u}, \tilde{v} \rangle = 0$ by the standard Hermitian metric of C^{n+1} , under the identification $(\tilde{u}, \tilde{v}) \equiv (\lambda\tilde{u}, \lambda\tilde{v})$ for all $\lambda \in C^1$, $\|\lambda\|=1$. Now we define the Hermitian metric $F: E(\tau_c(CP^n)) \times E(\tau_c(CP^n)) \rightarrow C^1$ by

$$F([\tilde{u}_1, \tilde{v}_1], [\tilde{u}_2, \tilde{v}_2]) = \langle \tilde{u}_1, \tilde{u}_2 \rangle \langle \tilde{v}_2, \tilde{v}_1 \rangle.$$

Then the total space of ν_c is

$$E(\nu_c) = \{[\bar{u}, \bar{v}] \in E(\tau_c(CP^n)) : \bar{u} \in C^n, \text{ and } F([\bar{u}, \bar{v}], [\bar{u}, \bar{v}_1]) = 0 \\ \text{for each } [\bar{u}, \bar{v}_1] \in E(\tau_c(CP^{n-1}))\},$$

that is, $E(\nu_c)$ consists of the elements $[\bar{u}, \bar{v}]$, where $\bar{v} = (0, \dots, 0, z_n)$. Therefore $E(\pi^*\nu_c)$ can be represented as the set of all pairs $[\bar{u}, \bar{v}]$ with $\|\bar{u}\| = 1$, $\bar{u} \in C^n$ and $\bar{v} = (0, \dots, 0, z_n)$ under the identification $(\bar{u}, \bar{v}) \equiv (\rho\bar{u}, \rho\bar{v})$, $\rho = \exp(2\pi i/p)$. Consider the open submanifold

$$\tilde{L}^n(p) = \{[z_0, \dots, z_n] \in L^n(p); |z_n| < 1\}$$

of $L^n(p)$; there is a diffeomorphism

$$g: \tilde{L}^n(p) \rightarrow E(\pi^*\nu_c)$$

given by

$$g([z_0, \dots, z_n]) = [(z_0/\lambda, \dots, z_{n-1}/\lambda), (0, \dots, 0, z_n/\lambda)], \lambda = \sqrt{\sum_{i=0}^{n-1} |z_i|^2},$$

that is, $\tilde{L}^n(p)$ is the tubular neighborhood of $L^{n-1}(p)$ in $L^n(p)$. We define the map

$$f: E(\pi^*\nu_c) \rightarrow \bar{\eta}',$$

by $f([z_0, \dots, z_{n-1}], (0, \dots, 0, z_n)) = ([z_0, \dots, z_{n-1}], z_n)$, where $\bar{\eta}'$ is a canonical complex line bundle over CP^{n-1} . Let h be a standard homeomorphism between the Thom complex of $\bar{\eta}'$ and CP^n . Then, for $[L^{n-1}(p), i] \in U_{2n-1}(L^n(p))$, we have

$$d(i)([z_0, \dots, z_n]) = \begin{cases} h \circ f \circ g([z_0, \dots, z_n]), & |z_n| \neq 1 \\ [0, \dots, 0, 1], & |z_n| = 1. \end{cases}$$

It follows that $\pi = d(i)$. Since $\rho(\pi^*\eta - 1_c) = [\pi]$, the proposition follows. q.e.d.

Kambe [2] showed that the order of $\pi^*(\eta - 1_c) \in \tilde{K}(L^n(p))$ is $p^{[(n-1)/(p-1)]+1}$. Then we have the following

Proposition 1.4. $[L^{n-1}(p), i] \in U_{2n-1}(BZ_p)$ is of order $p^{[(n-1)/(p-1)]+1}$.

2. The structure of $U_*(BZ_p)$.

We consider the $2n$ -skeleton $L_0^n(p)$ of $L_n(p)$, that is,

$$L_0^n(p) = s^1 \cup_p e^2 \cup e^3 \cup_p \dots \cup e^{2n-1} \cup_p e^{2n}.$$

Using the bordism exact sequence for a pair $(L^n(p), L_0^n(p))$, we have $U_k(L_0^n(p)) \approx U_k(L^n(p))$, for $k < 2n$. Therefore, for a large n

$$U_{2k+1}(L^n(p)) \approx \tilde{U}_{2k+1}(L^n(p)) \approx \tilde{U}_{2k+1}(L_0^n(p)), \quad U_{2k}(L^n(p)) \approx U_{2k}(L_0^n(p)).$$

The bordism spectral sequence $\{E_s^r, t\}$ for $L_0^n(p)$ is trivial and if $s+t=2k$, then

$E_{s,t}^2 \approx 0 (s \neq 0)$, $E_{0,2k}^2 \approx U_{2k}$. It follows immediately that $U_{2k}(L^n(p)) \approx U_{2k}$.

Lemma 2.1. *If $\alpha[L^0(p), i] = 0$ in $U_{2j+1}(L^n(p))$ for a large n and $\alpha \in U_{2j}$, then $\alpha \in pU_{2j}$.*

Proof. Since $U_{2j+1}(L^n(p)) \approx \tilde{U}_{2j+1}(L_0^n(p))$, we can assume that $\alpha[L^0(p), i] \in \tilde{U}_{2j+1}(L_0^n(p))$. Consider the reduced bordism spectral sequence $\{\tilde{E}_t^{r,s}\}$ for $L_0^n(p)$, which is trivial. There is a filtration $0 \subset J_{0,k} \subset J_{1,k-1} \subset \dots \subset J_{k,0} \approx \tilde{U}_k(L_0^n(p))$ with $J_{s,t}/J_{s-1,t+1} \approx \tilde{H}_s(L_0^n(p), U_t)$. The multiplication

$$m: \tilde{U}_s(L_0^n(p)) \otimes U_t \rightarrow \tilde{U}_{s+t}(L_0^n(p))$$

induces the following commutative diagram

$$\begin{CD} \tilde{U}_1(L_0^n(p)) \otimes U_{2j} = J_{1,0} \otimes U_{2j} @>\mu \otimes id>> \tilde{H}_1(L_0^n(p)) \otimes U_{2j} \\ @VVm_1V @VVm_2V \\ J_{1,2j} @>\mu'>> \tilde{H}_1(L_0^n(p), U_{2j}) \end{CD}$$

where μ is the edge homomorphism.

$\alpha \mu[L^0(p), i] = m_2(\mu \otimes id)([L^0(p), i] \otimes \alpha) = \mu' \circ m_1([L^0(p), i] \otimes \alpha) = \mu' \alpha[L^0(p), i] = 0$. On the other hand $\mu[L^0(p), i]$ is a generator of $\tilde{H}_1(L_0^n(p))$. Since $\tilde{H}_1(L_0^n(p))$ is p -torsion group, $\alpha \in pU_*$. q.e.d.

Lemma 2.2. *Suppose that X is an n -dimensional U -manifold. If $[M_1, f_1], [M_2, f_2] \in U_*(X)$ are the elements represented by embedding maps $f_k: M_k \rightarrow X$ ($k = 1, 2$). If the two embeddings are transversal to each other, then $D[M_1, f_1]D[M_2, f_2] = D[M_1 \cdot M_2, f_1 | M_1 \cdot M_2]$, where $M_1 \cdot M_2$ is intersection manifold of M_1 and M_2 in X .*

Proof. We can suppose that $M_1 \cdot M_2$ is a submanifold satisfying $N(M_1 \cdot M_2) = i_1^* N(M_1) \oplus i_2^* N(M_2)$, where $i_k: M_1 \cdot M_2 \rightarrow M_k$ ($k = 1, 2$) is the inclusion map and $N(M)$ is the normal bundle of M in X . $D[M_1 \cdot M_2, f_1 | M_1 \cdot M_2]$ is constructed by the bundle map

$$\begin{CD} N(M_1 \cdot M_2) @>\Delta>> N(M_1) \times N(M_2) @>>> EU(s) \times EU(t) @>>> EU(s+t) \\ @VVV @VVV @VVV @VVV \\ M_1 \cdot M_2 @>\Delta>> M_1 \times M_2 @>>> BU(s) \times BU(t) @>>> BU(s+t), \end{CD}$$

where Δ is a diagonal map, and s and t are the dimensions of $N(M_1)$ and $N(M_2)$ respectively. In view of the definition of multiplication in the cobordism group, we complete the proof.

Suppose that η is the canonical line bundle over CP^n , it follows from Lemma 2.2 that $\{c_1(\pi^* \eta)\}^k = D[L^{n-k}(p), i]$.

Mischenko obtained the following theorem [4], which plays an important

role to deduce some relations of the elements of $U_{2k-1}(BZ_p)$.

Theorem 2.3 (Mischenko). *For a complex line bundle ξ over a CW complex X , define a series $g(c_1(\xi))$ by*

$$g(c_1(\xi)) = \sum_{k \geq 0} \frac{x_k}{k+1} c_1(\xi)^{k+1} \in U^2(X) \otimes Q, \quad x_k = [CP^k].$$

This satisfies, for line bundles ξ and η , the relation

$$g(c_1(\xi \otimes \eta)) = g(c_1(\xi)) + g(c_1(\eta)).$$

Proposition 2.4. *There exists $\alpha_a \not\equiv 0 \pmod p$ such that*

$$p^a [L^{a(p-1)}(p), i] = \alpha_a [CP^{p-1}]^a [L^0(p), i].$$

Proof. The proof is by induction on a . Let η be the canonical complex line bundle over CP^p . By Theorem 2.3

$$g(c_1(\eta^p)) = pg(c_1(\eta)) = p \left\{ c_1(\eta) + \frac{x_1}{2} c_1(\eta)^2 + \dots + \frac{x_{p-1}}{p} c_1(\eta)^p \right\}$$

and

$$(p-1)!g(c_1(\eta^p)) = p!c_1(\eta) + p(p-1) \cdot \check{2} \cdot 1x_1c_1(\eta)^2 + \dots + (p-1)!x_{p-1}c_1(\eta)^p.$$

Since $U^*(CP^p)$ is torsion free, the above relation is an integral relation. Then, by the naturality of g and $(\pi^*\eta)^p = 1$,

$$p!c_1(\pi^*\eta) + p(p-1) \cdot \check{2} \cdot 1x_1c_1(\pi^*\eta)^2 + \dots + (p-1)!x_{p-1}c_1(\pi^*\eta)^p = 0.$$

Using Lemma 2.2,

$$p! [L^{p-1}(p), i] + p(p-1) \cdot \check{2} \cdot 1x_1 [L^{p-2}(p), i] + \dots + (p-1)!x_{p-1} [L^0(p), i] = 0.$$

Since the order of $[L^j(p), i]$ is p for $j < p-1$ and the order of $[L^{p-1}(p), i]$ is p^2 by Proposition 1.4,

$$p! [L^{p-1}(p), i] + (p-1)!x_{p-1} [L^0(p), i] = 0.$$

Since p is prime, the case $a=1$ follows. Suppose our assertion is true for $b < a$. Let ξ be the canonical line bundle over $CP^{a(p-1)+1}$. By Theorem 2.3,

$$g(c_1(\xi^p)) = p \left\{ c_1(\xi) + \frac{x_1}{2} c_1(\xi)^2 + \dots + \frac{x_{a(p-1)}}{a(p-1)+1} c_1(\xi)^{a(p-1)+1} \right\}.$$

Put $\{a(p-1)+1\}! = p^s m$, $m \not\equiv 0 \pmod p$. If $n! = p^u n'$, $n' \not\equiv 0 \pmod p$ then $u = \sum_{k \geq 1} [n/p^k]$. Hence

$$s = a \quad \text{if } a = p^r + p^{r-1} + \dots + 1, \quad s < a \quad \text{otherwise.}$$

Consider the following equation

$$Ag(c_1(\xi^p)) = Ap \left\{ c_1(\xi) + \frac{x_1}{2} c_1(\xi)^2 + \dots + \frac{x_{a(p-1)}}{a(p-1)+1} c_1(\xi)^{a(p-1)+1} \right\},$$

where $A = \{a(p-1)+1\}! p^{a-s-1}$.

This is an integral relation. Therefore, using $(\pi^* \xi)^p = 1$, the naturality of g and Lemma 2.2,

$$p^a m [L^{a(p-1)}(p), i] + \frac{p^a m}{2} x_1 [L^{a(p-1)-1}(p), i] + \dots + \frac{p^a m x_{a(p-1)}}{a(p-1)+1} [L^0(p), i] = 0.$$

Denote by $o([L^t(p), i])$ the order of $[L^t(p), i]$. Suppose that

$$t = a(p-1) - (p^k n - 1), \quad n \not\equiv 0 \pmod{p},$$

By Proposition 1.4,

$$\begin{aligned} o([L^t(p), i]) &= p^a \quad \text{if } k=1 \text{ and } n=1, \\ o([L^t(p), i]) &= p^v, \quad v < a - k + 1 \text{ otherwise.} \end{aligned}$$

Therefore,

$$p^a m [L^{a(p-1)}(p), i] + p^{a-1} m x_{p-1} [L^{(a-1)(p-1)}(p), i] = 0.$$

Since $m \not\equiv 0 \pmod{p}$, using the induction hypothesis, the proposition follows. q. e. d.

Let $\Gamma(p)$ be the polynomial subring of U_* generated by all $[Y_{2k}] \in U_{2k}$ with $k \neq p-1$. We note that $\Gamma(p)[CP^{p-1}] = U_*$.

Proposition 2.5. *Suppose we are given a relation*

$$\sum_{k=0}^n [L^k(p), i] [M^{2(l-k)}] = 0,$$

with $[M^{2(l-k)}] \in \Gamma(p)$. Then $[M^{2(l-k)}] \in p^{\lfloor k/(p-1) \rfloor + 1} \Gamma(p)$.

Proof. The proof is by induction on n . Lemma 2.1 implies that the case $n=0$ is true. Suppose our assertion is true for $m < n$. We consider

$$\sum_{k=0}^n [L^k(p), i] [M^{2(l-k)}] = 0 \tag{1}$$

Applying Smith homomorphism to this equation, we have

$$\sum_{k=0}^n [L^{k-1}(p), i] [M^{2(l-k)}] = 0.$$

By the induction hypothesis $[M^{2(l-k)}] = p^{\lfloor (k-1)/(p-1) \rfloor + 1} [N^{2(l-k)}]$. Since $\left[\frac{k-1}{p-1} \right]$

$= \left[\frac{k}{p-1} \right]$ for $k \neq a(p-1)$ and the order of $[L^k(p), i]$ is $p^{\lfloor k/(p-1) \rfloor + 1}$ by Proposition 1.4, the equation (1) becomes

$$\sum_a p^a [L^{a(p-1)}(p), i] [N^{2l-2a(p-1)}] = 0.$$

From Proposition 2.4,

$$\sum_a \alpha_a [N^{2l-2a(p-1)}] [CP^{p-1}]^a [L^0(p), i] = 0.$$

Since $\alpha_a \not\equiv 0 \pmod p$, it follows from Lemma 2.1 that $[N^{2l-2a(p-1)}] \in pU_*$. This completes the proof.

Let $\Gamma_{2k}(p)$ consist of $2k$ -dimensional homogenous polynomial. Finally we have the following

Theorem 2.6. *The homomorphism*

$$\Theta: \sum_{k=0}^n \Gamma_{2(n-k)}(p) / p^{\lfloor k/(p-1) \rfloor + 1} \Gamma_{2(n-k)}(p) \rightarrow U_{2n+1}(BZ_p)$$

given by $\Theta(\sum_{k=0}^n [M^{2(n-k)}]) = \sum_{k=0}^n [M^{2(n-k)}][L^k(p), i]$ is isomorphism.

Proof. The Proposition 2.5 is precisely the statement that Θ is monomorphism. To check that Θ is epimorphism, we compute the order of the group

$$\sum_{k=0}^n \Gamma_{2(n-k)}(p) / p^{\lfloor k/(p-1) \rfloor + 1} \Gamma_{2(n-k)}(p),$$

and compare it with that of $U_{2n+1}(BZ_p)$. The former is p^τ , $\tau = \sum_{k=0}^n t_k \left\{ \left[\frac{k}{p-1} \right] + 1 \right\}$, where t_k is the number of partitions of k , containing no $(p-1)$, the latter is p^σ , $\sigma = \sum_{k=0}^n s_k$, where s_k is the number of partitions of k . Now

$$\begin{aligned} \sigma &= \sum_{k=0}^n s_k = \sum_k \sum_a t_{k-a(p-1)} = \sum_j (\max \{a \mid j = k - a(p-1)\} + 1) t_j \\ &= \sum_j \left(\left[\frac{j}{p-1} \right] + 1 \right) t_j = \tau. \end{aligned}$$

Thus Θ is an isomorphism. q. e. d.

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