Journal de Théorie des Nombres
de Bordeaux **17** (2005), 779–786

On the ring of p-integers of a cyclic p-extension over a number field

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Résumé. Soit p un nombre premier. On dit qu'une extension finie, galoisienne, N/F d'un corps de nombres F, à groupe de Galois G, admet une base normale p-entière (p-NIB en abrégé) si $\mathcal{O}'_N$ est libre de rang un sur l'anneau de groupe $\mathcal{O}'_F[G]$ où $\mathcal{O}'_F = \mathcal{O}_F[1/p]$ désigne l'anneau des p-entiers de F. Soit $m = p^e$ une puissance de p et N/F une extension cyclique de degré m. Lorsque $\zeta_m \in F^\times$, nous donnons une condition nécessaire et suffisante pour que N/F admette une p-NIB (Théorème 3). Lorsque $\zeta_m \notin F^\times$ et $p \nmid [F(\zeta_m) : F]$, nous montrons que N/F admet une p-NIB si et seulement si $N(\zeta_m)/F(\zeta_m)$ admet p-NIB (Théorème 1). Enfin, si p divise $[F(\zeta_m) : F]$, nous montrons que la propriété de descente n'est plus vraie en général (Théorème 2).

Abstract. Let p be a prime number. A finite Galois extension N/F of a number field F with group G has a normal p-integral basis (p-NIB for short) when $\mathcal{O}'_N$ is free of rank one over the group ring $\mathcal{O}'_F[G]$. Here, $\mathcal{O}'_F = \mathcal{O}_F[1/p]$ is the ring of p-integers of F. Let $m = p^e$ be a power of p and N/F a cyclic extension of degree m. When $\zeta_m \in F^\times$, we give a necessary and sufficient condition for N/F to have a p-NIB (Theorem 3). When $\zeta_m \notin F^\times$ and $p \nmid [F(\zeta_m) : F]$, we show that N/F has a p-NIB if and only if $N(\zeta_m)/F(\zeta_m)$ has a p-NIB (Theorem 1). When p divides $[F(\zeta_m) : F]$, we show that this descent property does not hold in general (Theorem 2).

1. Introduction

We fix a prime number p throughout this article. For a number field F, let $\mathcal{O}_F$ be the ring of integers, and $\mathcal{O}'_F = \mathcal{O}_F[1/p]$ the ring of p-integers of F. A finite Galois extension N/F with group G has a normal integral basis (NIB for short) when $\mathcal{O}_N$ is free of rank one over the group ring $\mathcal{O}_F[G]$. It has a normal p-integral basis (p-NIB for short) when $\mathcal{O}'_N$ is free of rank one over $\mathcal{O}'_F[G]$. For a cyclic p-extension N/F unramified outside p, several results on p-NIB are given in the lecture note of Greither [5]. Let N/F

Manuscrit reçu le 4 septembre 2003.

be such a cyclic extension of degree $m = p^e$. In particular, it is known (A) that when $\zeta_m \in F^\times$, it has a p-NIB if and only if $N = F(\epsilon^{1/m})$ for some unit ϵ of $\mathcal{O}'_F$ ([5, Proposition **0**.6.5]), and (B) that when $\zeta_m \notin F^\times$, it has a p-NIB if and only if the pushed-up extension $N(\zeta_m)/F(\zeta_m)$ has a p-NIB ([5, Theorem I.2.1]). Here, ζ_m is a fixed primitive m-th root of unity. These results for the unramified case form a basis of the study of a normal p-integral basis problem for $\mathbb{Z}_p$-extensions in Kersten and Michalicek [12], [5] and Fleckinger and Nguyen-Quang-Do [2]. The purpose of this article is to give some corresponding results for the ramified case.

Let $m = p^e$ be a power of p, F a number field with $\zeta_m \in F^\times$. In Section 2, we give a necessary and sufficient condition (Theorem 3) for a cyclic Kummer extension N/F of degree m to have a p-NIB. It is given in terms of a Kummer generator of N, but rather complicated compared with the unramified case. We also give an application of this criterion.

When $\zeta_m \notin F^\times$ and $p \nmid [F(\zeta_m) : F]$, we show the following descent property in Section 3.

Theorem 1. *Let $m = p^e$ be a power of a prime number p, F a number field with $\zeta_m \notin F^\times$, and $K = F(\zeta_m)$. Assume that $p \nmid [K : F]$. Then, a cyclic extension N/F of degree m has a p-NIB if and only if NK/K has a p-NIB.*

When p divides $[K : F]$, this type of descent property does not hold in general. Actually, we show the following assertion in Section 4. Let Cl'_F be the ideal class group of the Dedekind domain $\mathcal{O}'_F = \mathcal{O}_F[1/p]$.

Theorem 2. *Let F be a number field with $\zeta_p \in F^\times$ but $\zeta_{p^2} \notin F^\times$, and $K = F(\zeta_{p^2})$. Assume that there exists a class $\mathcal{C} \in Cl'_F$ of order p which capitulates in $\mathcal{O}'_K$. Then, there exist infinitely many cyclic extensions N/F of degree p^2 with $N \cap K = F$ such that* (i) *N/F has no p-NIB but* (ii) *NK/K has a p-NIB.*

At the end of Section 4, we see that there are several examples of p and F satisfying the assumption of Theorem 2.

Remark 1. In Theorem 1, the condition $p \nmid [K : F]$ means that $[K : F]$ divides $p - 1$. Further, p must be an odd prime as $p \nmid [K : F]$.

Remark 2. As for the descent property of normal integral bases in the usual sense, the following facts are known at present. Let F be a number field with $\zeta_p \notin F^\times$, and $K = F(\zeta_p)$. For a cyclic extension N/F of degree p unramified at all finite prime divisors, it has a NIB if and only if NK/K has a NIB. This was first proved by Brinkhuis [1] when $p = 3$ and F is an imaginary quadratic field, and then by the author [7] for the general case. When $p = 3$, for a tame cyclic cubic extension N/F,it has a NIB if and only if NK/K has a NIB. This was first proved by Greither [6, Theorem 2.2] when $p = 3$ is unramified in $F/\mathbb{Q}$, and then by the author [9] for the general case.

2. A condition for having a p-NIB

In [4, Theorem 2.1], Gómez Ayala gave a necessary and sufficient condition for a tame Kummer extension of prime degree to have a NIB (in the usual sense). In [8, Theorem 2], we generalized it for a tame cyclic Kummer extension of arbitrary degree. The following is a p-integer version of these results. Let $m = p^e$ be a power of a prime number p, and F a number field. Let $\mathfrak{A}$ be an m-th power free integral ideal of $\mathcal{O}'_F$. Namely, $\wp^m \nmid \mathfrak{A}$ for all prime ideals $\wp$ of $\mathcal{O}'_F$. We can uniquely write

$$\mathfrak{A} = \prod_{i=1}^{m-1} \mathfrak{A}_i^i$$

for some square free integral ideals $\mathfrak{A}_i$ of $\mathcal{O}'_F$ relatively prime to each other. As in [4, 8], we define the associated ideals $\mathfrak{B}_j$ of $\mathfrak{A}$ as follows.

$$\mathfrak{B}_j = \prod_{i=1}^{m-1} \mathfrak{A}_i^{[ij/m]} \quad (0 \leq j \leq m-1). \tag{1}$$

Here, for a real number x, $[x]$ denotes the largest integer $\leq x$. By definition, we have $\mathfrak{B}_0 = \mathfrak{B}_1 = \mathcal{O}'_F$.

Theorem 3. *Let $m = p^e$ be a power of a prime number p, and F a number field with $\zeta_m \in F^\times$. Then, a cyclic Kummer extension N/F of degree m has a p-NIB if and only if there exists an integer $a \in \mathcal{O}'_F$ with $N = F(a^{1/m})$ such that* (i) *the principal integral ideal $a\mathcal{O}'_F$ is m-th power free and* (ii) *the ideals associated to $a\mathcal{O}'_F$ by* (1) *are principal.*

The proof of this theorem goes through exactly similarly to the proof of [8, Theorem 2]. So, we do not give its proof. (In the setting of this theorem, the conditions (iv) and (v) in [8, Theorem 2] are not necessary as m is a unit of $\mathcal{O}'_F$.)

It is easy to see that the assertion (A) mentioned in Section 1 follows from this theorem. The following is an immediate consequence of Theorem 3.

Corollary 1. *Let m and F be as in Theorem 3. Let $a \in \mathcal{O}'_F$ be an integer such that the principal integral ideal $a\mathcal{O}'_F$ is square free. Then, the cyclic extension $F(a^{1/m})/F$ has a p-NIB.*

Let H_F be the Hilbert class field of F. The p-Hilbert class field H'_F of F is by definition the maximal intermediate field of H_F/F in which all prime ideals of $\mathcal{O}_F$ over p split completely. Let Cl_F be the ideal class group of

F in the usual sense, and P the subgroup of Cl_F generated by the classes containing a prime ideal over p. Then, we naturally have $Cl'_F \cong Cl_F/P$. Hence, by class field theory, Cl'_F is canonically isomorphic to $\mathrm{Gal}(\mathrm{H}'_\mathrm{F}/\mathrm{F})$. It is known that any ideal of $\mathcal{O}'_F$ capitulates in $\mathcal{O}'_{H_F}$. This is shown exactly similarly to the classical principal ideal theorem for H_F/F given in Koch [13, pp. 103-104]. Now, we can derive the following "capitulation" result from Theorem 3.

Corollary 2. *Let m and F be as in Theorem 3. Then, for any abelian extension N/F of exponent dividing m, the pushed-up extension NH'_F/H'_F has a p-NIB. In particular, if $h'_F = |Cl'_F| = 1$, any abelian extension N/F of exponent dividing m has a p-NIB.*

Proof. For brevity, we write $H = H'_F$. For each prime ideal $\mathfrak{L}$ of $\mathcal{O}'_F$, we can choose an integer $\omega_\mathfrak{L} \in \mathcal{O}'_H$ such that $\mathfrak{L}\mathcal{O}'_H = \omega_\mathfrak{L}\mathcal{O}'_H$ by the principal ideal theorem mentioned above. Let $\epsilon_1, \cdots, \epsilon_r$ be a system of fundamental units of $\mathcal{O}'_H$, and ζ a generator of the group of roots of unity in H. Let N/F be an arbitrary abelian extension of exponent dividing m. Then, we have

$$N = F(a_1^{1/m}, \cdots, a_s^{1/m})$$

for some $a_i \in \mathcal{O}'_F$. We see that NH is contained in

$$\widetilde{N} = H\left(\zeta^{1/m}, \epsilon_i^{1/m}, \omega_\mathfrak{L}^{1/m} \mid 1 \leq i \leq r, \mathfrak{L}|a_1 \cdots a_s\right).$$

Here, $\mathfrak{L}$ runs over the prime ideals of $\mathcal{O}'_F$ dividing $a_1 \cdots a_s$. As H/F is unramified, the principal ideal $\mathfrak{L}\mathcal{O}'_H = \omega_\mathfrak{L}\mathcal{O}'_H$ is square free. Hence, by Corollary 1, the extensions

$$(2) \qquad H(\zeta^{1/m})/H, \quad H(\epsilon_i^{1/m})/H, \quad H(\omega_\mathfrak{L}^{1/m})/H \quad \text{with } \mathfrak{L}|a_1 \cdots a_s$$

have a p-NIB. As the ideal $\omega_\mathfrak{L}\mathcal{O}'_H = \mathfrak{L}\mathcal{O}'_H$ is square free, the extension $H(\omega_\mathfrak{L}^{1/m})/H$ is fully ramified at the primes dividing $\mathfrak{L}$ and unramified at other prime ideals of $\mathcal{O}'_H$. Therefore, we see from the choice of ζ and ϵ_i that the extensions in (2) are linearly independent over H and that the ideal generated by the relative discriminants of any two of them equals $\mathcal{O}'_H$. Therefore, the composite $\widetilde{N}/H$ has a p-NIB by a classical theorem on rings of integers (cf. Fröhlich and Taylor [3, III (2.13)]). Hence, NH/H has a p-NIB as $NH \subseteq \widetilde{N}$. □

Remark 3. For the ring of integers in the usual sense, a result corresponding to this corollary is obtained in [8, Theorem 1].

3. Proof of Theorem 1

The "only if" part follows immediately from [3, III, (2.13)].

Let us show the "if" part. Let $m = p^e$, F, K be as in Theorem 1. Here,

p is an odd prime number (see Remark 1). Let N/F be a cyclic extension of degree m, $L = NK$, and $G = \mathrm{Gal(L/K)} = \mathrm{Gal(N/F)}$. Assume that $\mathcal{O}'_L = \mathcal{O}'_K[G] \cdot \omega$ for some $\omega \in \mathcal{O}'_L$. To prove that N/F has a p-NIB, it suffices to show that we can choose $W \in \mathcal{O}'_N$ such that $\mathcal{O}'_L = \mathcal{O}'_K[G] \cdot W$. Actually, when this is the case, we easily see that $\mathcal{O}'_N = \mathcal{O}'_F[G] \cdot W$. Let $\Delta_F = \mathrm{Gal(L/N)} = \mathrm{Gal(K/F)}$ and $\ell = |\Delta_F|$ (≥ 2). As $p \nmid [K : F]$, ℓ divides $p-1$ (see Remark 1). We fix a primitive m-th root of unity: $\zeta = \zeta_m$. Let σ be a fixed generator of the cyclic group Δ_F of order ℓ, and let $\kappa \in \mathbb{Z}$ be an integer with $\zeta^\sigma = \zeta^\kappa$, which is uniquely determined modulo m. For an integer $x \in \mathbb{Z}$, let $[x]_{p^f}$ be the class in $\mathbb{Z}/p^f = \mathbb{Z}/p^f\mathbb{Z}$ represented by x. For $1 \leq f \leq e$, the class $[\kappa]_{p^f}$ in the multiplicative group $(\mathbb{Z}/p^f)^\times$ is of order ℓ. We put

$$t_f = p^{f-1}(p-1)/\ell \ (\in \mathbb{Z}).$$

For each $1 \leq f \leq e$, we choose integers $r_{f,1}, \cdots, r_{f,t_f} \in \mathbb{Z}$ so that their classes modulo p^f form a complete set of representatives of the quotient $(\mathbb{Z}/p^f)^\times/\langle[\kappa]_{p^f}\rangle$. Then, we have

$$\{[0]_m,\ [p^{e-f} r_{f,i} \kappa^{j-1}]_m \mid 1 \leq f \leq e,\ 1 \leq i \leq t_f,\ 1 \leq j \leq \ell\} = \mathbb{Z}/m. \tag{3}$$

For brevity, we put

$$a(f,\, i,\, j) = p^{e-f} r_{f,i} \kappa^{j-1}.$$

Fixing a generator g of G, we define the resolvents α_0 and $\alpha_{f,i,j}$ of ω by

$$\alpha_0 = \sum_{\lambda=0}^{m-1} \omega^{g^\lambda} \quad \text{and} \quad \alpha_{f,i,j} = \sum_{\lambda=0}^{m-1} \zeta^{-a(f,i,j)\lambda} \omega^{g^\lambda},$$

for each $1 \leq f \leq e$, $1 \leq i \leq t_f$ and $1 \leq j \leq \ell$. By (3), we see that the determinant of the $m \times m$ matrix of the coefficients of ω^{g^λ} in the above m equalities is divisible only by prime ideals of $\mathcal{O}_K$ dividing p. Hence, it is a unit of $\mathcal{O}'_K$. Therefore, from the assumption $\mathcal{O}'_L = \mathcal{O}'_K[G] \cdot \omega$, we obtain

$$\mathcal{O}'_L = \mathcal{O}'_K \alpha_0 + \sum_{f,i,j} \mathcal{O}'_K \alpha_{f,i,j}. \tag{4}$$

Let ${\mathcal{O}'_L}^{(0)} = \mathcal{O}'_K$, and let ${\mathcal{O}'_L}^{(f,i,j)}$ be the additive group of integers $x \in \mathcal{O}'_L$ such that $x^g = \zeta^{a(f,i,j)} x$. As $\zeta^\sigma = \zeta^\kappa$, we see that

$${\mathcal{O}'_L}^{(f,i,j)} = ({\mathcal{O}'_L}^{(f,i,1)})^{\sigma^{j-1}}. \tag{5}$$

As is easily seen, we have $\alpha_0 \in \mathcal{O}'_K$ and $\alpha_{f,i,j} \in {\mathcal{O}'_L}^{(f,i,j)}$. From $\mathcal{O}'_L = \mathcal{O}'_K[G] \cdot \omega$, we see that

$${\mathcal{O}'_L}^{(0)} = \mathcal{O}'_K = \mathcal{O}'_K \alpha_0 \quad \text{and} \quad {\mathcal{O}'_L}^{(f,i,j)} = \mathcal{O}'_K \alpha_{f,i,j} = \mathcal{O}'_K \alpha_{f,i,1}^{\sigma^{j-1}}.$$

Here, the last equality holds by (5). Therefore, from (4), we obtain

$$\mathcal{O}'_L = \mathcal{O}'_K + \sum_{f,i,j} \mathcal{O}'_K \alpha_{f,i,1}^{\sigma^{j-1}}. \tag{6}$$

Now, we put

$$W = 1 + \sum_{f,i,j} \alpha_{f,i,1}^{\sigma^{j-1}} = 1 + \sum_{f,i} \mathrm{Tr}_{L/N}(\alpha_{f,i,1}) \in \mathcal{O}'_N.$$

Here, $\mathrm{Tr}_{L/N}$ denotes the trace map. As $\alpha_{f,i,1}^{\sigma^{j-1}} \in \mathcal{O}'^{(f,i,j)}_L$, we have

$$W^{g^\lambda} = 1 + \sum_{f,i,j} \zeta^{a(f,i,j)\lambda} \alpha_{f,i,1}^{\sigma^{j-1}}$$

for $0 \le \lambda \le m-1$. We see that the determinant of the $m \times m$ matrix of the coefficients of $\alpha_{f,i,1}^{\sigma^{j-1}}$ in the above m equalities is a unit of $\mathcal{O}'_K$. Hence, by (6), we obtain $\mathcal{O}'_L = \mathcal{O}'_K[G] \cdot W$. Therefore, as $W \in \mathcal{O}'_N$, N/F has a p-NIB. □

4. Proof of Theorem 2

Let F, K be as in Theorem 2, and $\Delta_F = \mathrm{Gal(K/F)}$. As $\zeta_p \in F^\times$, we can choose a generator σ of the cyclic group Δ_F of order p so that $\zeta_{p^2}^\sigma = \zeta_{p^2}^\kappa$ with $\kappa = 3$ or $1+p$ according to whether $p = 2$ or $p \ge 3$. When $p \ge 3$, we put

$$D = \sum_{i=0}^{p-1} \kappa^i \sigma^{p-1-i} \ (\in \mathbb{Z}[\Delta_F]).$$

The following lemma is an exercise in Galois theory.

Lemma. *Under the above setting, let x be a nonzero element of K. We put*

$$a = \begin{cases} x x^{3\sigma}, & \text{for } p = 2, \\ x^D = x^{\sigma^{p-1}} x^{\kappa\sigma^{p-2}} \cdots x^{\kappa^{p-2}\sigma} x^{\kappa^{p-1}}, & \text{for } p \ge 3. \end{cases} \tag{7}$$

Let $L = K(a^{1/p^2})$. Assume that $a \notin (K^\times)^p$. Then, L/F is an abelian extension of type (p, p^2). Hence, there exists a cyclic extension N/F of degree p^2 with $N \cap K = F$ and $L = NK$.

Proof of Theorem 2. Let $\mathcal{C}$ be as in Theorem 2, and $\mathfrak{Q}$ a prime ideal of $\mathcal{O}'_F$ contained in $\mathcal{C}$. By the assumption of Theorem 2, $\mathfrak{Q}\mathcal{O}'_K = \beta\mathcal{O}'_K$ is a principal ideal. Let $\mathfrak{P} = \alpha\mathcal{O}'_K$ be an arbitrary principal prime ideal of $\mathcal{O}'_K$ of degree one in K/F relatively prime to $\mathfrak{Q}$, and let $\wp = \mathfrak{P} \cap \mathcal{O}'_F$. Then, $\wp$ is a prime ideal of $\mathcal{O}'_F$ splitting completely in K. Let $x = \alpha\beta$, and define an integer a by (7). As $\mathfrak{Q}\mathcal{O}'_K = \beta\mathcal{O}'_K$ is invariant under the action of σ, we have

$$a\mathcal{O}'_K = \alpha\alpha^{3\sigma}\beta^4\mathcal{O}'_K \quad \text{or} \quad \alpha^{\sigma^{p-1}}\alpha^{\sigma^{p-2}\kappa} \cdots \alpha^{\sigma\kappa^{p-2}}\alpha^{\kappa^{p-1}}\beta^T\mathcal{O}'_K$$

according to whether $p = 2$ or $p \geq 3$. Here,

$$T = 1 + \kappa + \cdots + \kappa^{p-1}.$$

For $p \geq 3$, since $\kappa^i \equiv 1 + ip$, $T \equiv p \bmod p^2$, the last term equals

$$\prod_{i=0}^{p-1} \alpha^{\sigma^{p-1-i}(1+ip)} \beta^p X^{p^2} \mathcal{O}'_K$$

for some $X \in \mathcal{O}'_K$. We may as well replace a with a/β^4 (resp. a/X^{p^2}) for $p = 2$ (resp. $p \geq 3$). Then, it follows that

$$a\mathcal{O}'_K = \alpha\alpha^{3\sigma}\mathcal{O}'_K \quad \text{or} \quad \prod_{i=0}^{p-1} \alpha^{\sigma^{p-1-i}(1+ip)} \beta^p \mathcal{O}'_K \tag{8}$$

according to whether $p = 2$ or $p \geq 3$. In particular, we see that $a \notin (K^\times)^p$ as $\wp$ splits completely in K and $\mathfrak{P} = \alpha\mathcal{O}'_K$ is a prime ideal of $\mathcal{O}'_K$ over $\wp$. Then, by the lemma, $L = K(a^{1/p^2})$ is of degree p^2 over K, and there exists a cyclic extension N/F of degree p^2 with $N \cap K = F$ and $NK = L$. We see from (8) and Theorem 3 that L/K has a p-NIB. Let us show that N/F has no p-NIB. For this, assume that it has a p-NIB. Let N_1 be the intermediate field of N/F of degree p. By the assumption, N_1/F has a p-NIB. We see from (7) and $\kappa \equiv 1 \bmod p$ that $N_1K = K(b^{1/p})$ with

$$b = xx^\sigma \cdots x^{\sigma^{p-1}}.$$

As $b \in \mathcal{O}'_F$ and $\zeta_p \in F^\times$, it follows that $N_1 = F((\zeta_p^s b)^{1/p})$ for some $0 \leq s \leq p-1$. Since $x\mathcal{O}'_K = \mathfrak{P}\mathfrak{Q}\mathcal{O}'_K$, we have $b\mathcal{O}'_F = \wp\mathfrak{Q}^p$. As N_1/F has a p-NIB, it follows from Theorem 3 that there exists an integer $c \in \mathcal{O}'_F$ with $N_1 = F(c^{1/p})$ such that $c\mathcal{O}'_F$ is p-th power free. Hence, $c = (\zeta_p^s b)^r y^p$ for some $1 \leq r \leq p-1$ and $y \in F^\times$. We have $c\mathcal{O}'_F = \wp^r(y\mathfrak{Q}^r)^p$. As the integral ideal $c\mathcal{O}'_F$ is p-th power free, we must have $y\mathfrak{Q}^r = \mathcal{O}'_F$. This is a contradiction as the class $\mathcal{C}$ containing $\mathfrak{Q}$ is of order p. □

We see in the below that there are many examples of p and F satisfying the assumption of Theorem 2.

Let $p = 2$. Let q_1, q_2 be prime numbers with $q_1 \equiv q_2 \equiv -1 \bmod 4$ and $q_1 \neq q_2$, and let $F = \mathbb{Q}(\sqrt{-q_1q_2})$. Then, the imaginary quadratic field F satisfies the assumption of Theorem 2. The reason is as follows. Let $\mathfrak{Q}$ be the unique prime ideal of $\mathcal{O}'_F$ over q_1. We see that the class $\mathcal{C} = [\mathfrak{Q}] \in Cl'_F$ is of order 2 from genus theory. Let $K = F(\sqrt{-1}) = F(\sqrt{q_1q_2})$ and $k = \mathbb{Q}(\sqrt{q_1q_2})$. By genus theory, the class number of k in the usual sense is odd. Hence, we have $q_1\mathcal{O}_k = (\alpha\mathcal{O}_k)^2$ for some integer α. Therefore, $\mathfrak{Q}\mathcal{O}'_K = \alpha\mathcal{O}'_K$, and the class $\mathcal{C}$ capitulates in $\mathcal{O}'_K$.

Let us deal with the case $p \geq 3$. Let p be an odd prime number, k a real quadratic field in which p remains prime, $F = k(\zeta_p)$, and $K = F(\zeta_{p^2})$. Let

$\mathbf{B}_1/\mathbb{Q}$ be the unique cyclic extension of degree p unramified outside p, and $k_1 = k\mathbf{B}_1$. Clearly, we have $K = F\mathbf{B}_1$. In the tables in Sumida and the author [10, 11], we gave many examples of p and k having an ideal class $\mathcal{C} \in Cl_k$ of k which is of order p and capitulates in k_1. (More precisely, real quadratic fields in the rows "$n_0 = 0$" and "$n_0 = 1$" of the tables satisfy the condition.) For such a class $\mathcal{C}$, the lift $\mathcal{C}_F \in Cl_F$ to F is of order p and it capitulates in K. As p remains prime in k, there is only one prime ideal of F (resp. K) over p, and it is a principal ideal. Hence, we have $Cl_F = Cl'_F$ and $Cl_K = Cl'_K$. Thus, we obtain many examples of $p \geq 3$ and F satisfying the assumption of Theorem 2.

Acknowledgements. The author thanks the referee for valuable suggestions which improved the presentation of the paper. The author was partially supported by Grant-in-Aid for Scientific Research (C) (No. 16540033), the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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