

# ANNIHILATION OF $\mathrm{tor}_{\mathbb{Z}_p}(\mathcal{G}_{K,S}^{\mathrm{ab}})$ FOR REAL ABELIAN EXTENSIONS

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ABSTRACT. Let  $K$  be a real abelian extension of  $\mathbb{Q}$ . Let  $p$  be a prime number,  $S$  the set of  $p$ -places of  $K$  and  $\mathcal{G}_{K,S}$  the Galois group of the maximal  $S \cup \{\infty\}$ -ramified pro- $p$ -extension of  $K$ . We revisit the problem of annihilation of the  $p$ -torsion group  $\mathcal{T}_K := \mathrm{tor}_{\mathbb{Z}_p}(\mathcal{G}_{K,S}^{\mathrm{ab}})$  initiated by us and Oriat then systematized in our paper on the construction of  $p$ -adic  $L$ -functions in which we obtained a canonical ideal annihilator of  $\mathcal{T}_K$  in full generality (1978–1981). Afterwards (1992–2014) some annihilators, using cyclotomic units, were proposed by Solomon, Belliard–Nguyen Quang Do, Nguyen Quang Do–Nicolas, All, Belliard–Martin. In this text, we improve our original papers and show that, in general, the Solomon elements are not optimal and/or partly degenerated. We obtain, whatever  $K$  and  $p$  (Theorem 9.4), an universal non-degenerated annihilator in terms of  $p$ -adic logarithms of cyclotomic numbers related to  $L_p$ -functions at  $s = 1$ . Some computations are given with PARI programs; the case  $p = 2$  is analyzed and illustrated in degrees 2, 3, 4 to test a conjecture.

## 1. INTRODUCTION

Let  $K/\mathbb{Q}$  be a real abelian extension of Galois group  $G_K$ . Let  $p$  be a prime number,  $S$  the set of  $p$ -places of  $K$ , and  $\mathcal{G}_{K,S}$  the Galois group of the maximal  $S$ -ramified in the ordinary sense (i.e., unramified outside  $p$  and  $\infty$ ) pro- $p$ -extension of  $K$ .

We revisit the classical problem of annihilation of the so-called  $\mathbb{Z}_p[G_K]$ -module  $\mathcal{T}_K := \mathrm{tor}_{\mathbb{Z}_p}(\mathcal{G}_{K,S}^{\mathrm{ab}})$ , as dual of  $H^2(\mathcal{G}_{K,S}, \mathbb{Z}_p(0))$ . This was initiated by us [12] (1979) and improved by Oriat [21] (1981). Then in our paper [13] (1978/79) on the construction of  $p$ -adic  $L$ -functions (via an “arithmetic Mellin transform” from the “Spiegel involution” of suitable Stickelberger elements) we obtained incidentally a canonical ideal annihilator  $\mathcal{A}_K$  of  $\mathcal{T}_K$  in full generality, but our purpose, contrary to the present work, was the semi-simple case with  $p$ -adic characters; this aspect has then been outdated by the “principal theorems” of Ribet–Mazur–Wiles–Kolyvagin–Greither (refer for instance to the bibliography of [14]) and many other contributions.

Afterwards some annihilators, using cyclotomic units, were proposed by Solomon [25] (1992), Belliard–Nguyen Quang Do [5] (2005), Nguyen Quang Do–Nicolas [20] (2011), All [1] (2013), Belliard–Martin [4] (2014), using techniques of Sinnott, Rubin, Thaine, Coleman, from Iwasawa’s theory.

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In this text, we translate into english the above 1978–1981’s papers, written in french with tedious classical techniques, then we show that, in general, the Solomon elements  $\Psi_K$  are often degenerated regarding the annihilator  $\mathcal{A}_K$ , even for cyclic fields, and explain the origin of this gap due to trivialization of some Euler factors.

We obtain, whatever  $K$  and  $p$  (Theorem 9.4), an universal non-degenerated annihilator  $\mathcal{A}_K$ , in terms of  $p$ -adic logarithms of cyclotomic numbers, perhaps the best possible regarding these classical methods, but probably too general to cover all the possible Galois structures of  $\mathcal{T}_K$ , which raises the question of the existence of a better theorem than Stickelberger’s one.

We must say that the question of annihilation of  $\mathcal{T}_K$ , *in full generality*, is not of a crucial interest since numerical experiments show that the results are far to give the precise Galois structure of  $\mathcal{T}_K$  (e.g., in direction of its Fitting ideal), but it seems to us that many (all ?) papers are based on the classical reasoning with Kummer’s theory and Leopoldt’s Spiegel involution, even translated into Iwasawa’s theory, without practical analysis (e.g., with extensive numerical illustrations) of the results.

Thus, we perform some computations given with PARI programs [22] to analyse the quality of such annihilators, which is in general not addressed by papers dealing with Iwasawa’s theory. We consider in a large part the case  $p = 2$ , illustrated in degrees 2, 3, 4 to test the Conjecture 5.7.

## 2. NOTATIONS AND RECALLS ON $p$ -RAMIFICATION THEORY

Let  $K$  be a real abelian number field of degree  $d$ , of Galois group  $G_K$ , and let  $p \geq 2$  be a prime number; we denote by  $S_p =: S$  the set of prime ideals of  $K$  dividing  $p$ . Let  $\mathcal{G}_{K,S}$  be the Galois group of the maximal  $S \cup \{\infty\}$ -ramified pro- $p$ -extension of  $K$  and let  $H_K^{\text{pr}}$  be the maximal abelian  $S \cup \{\infty\}$ -ramified pro- $p$ -extension of  $K$ . Put  $\mathcal{G}_{K,S}^{\text{ab}} =: \mathcal{G}_K^{\text{ab}}$  and (e.g., [8, Chapter III, § (c)]):

$$\mathcal{T}_K := \text{tor}_{\mathbb{Z}_p}(\mathcal{G}_K^{\text{ab}}) = \text{Gal}(H_K^{\text{pr}}/K_\infty)$$

where  $K_\infty = K\mathbb{Q}_\infty$  is the cyclotomic  $\mathbb{Z}_p$ -extension of  $K$ ; so:

$$\mathcal{G}_K^{\text{ab}} \simeq \mathbb{Z}_p \oplus \mathcal{T}_K$$

since, in the abelian case, Leopoldt’s conjecture is true.

We denote by  $F$  an extension of  $K$  such that  $H_K^{\text{pr}}$  is the direct compositum of  $K_\infty$  and  $F$  over  $K$ , then by  $\mathcal{C}_K^\infty$  the subgroup of  $\mathcal{C}_K$  corresponding, by class field theory, to  $\text{Gal}(H_K/K_\infty \cap H_K)$ , where  $H_K$  is the  $p$ -Hilbert class field. We have (where  $\sim$  means “equality up to a  $p$ -adic unit”):

$$(2.1) \quad \#\mathcal{C}_K^\infty \sim \frac{\#\mathcal{C}_K}{[H_K \cap K_\infty : K]} \sim \#\mathcal{C}_K \cdot \frac{[K \cap \mathbb{Q}_\infty : \mathbb{Q}]}{e_p} \cdot \frac{2}{\#(\langle -1 \rangle \cap N_{K/\mathbb{Q}}(U_K))},$$

where  $e_p$  is the ramification index of  $p$  in  $K/\mathbb{Q}$  [8, Theorem III.2.6.4].

For each  $\mathfrak{p} \mid p$ , let  $K_{\mathfrak{p}}$  be the  $\mathfrak{p}$ -completion of  $K$  and  $\bar{\mathfrak{p}}$  the corresponding prime ideal of the ring of integers of  $K_{\mathfrak{p}}$ ; then let:

$$U_K := \left\{ u \in \bigoplus_{\mathfrak{p}|p} K_{\mathfrak{p}}^\times, u = 1 + x, x \in \bigoplus_{\mathfrak{p}|p} \bar{\mathfrak{p}} \right\} \quad \& \quad W_K := \text{tor}_{\mathbb{Z}_p}(U_K),$$

the  $\mathbb{Z}_p$ -module (of  $\mathbb{Z}_p$ -rank  $d = [K : \mathbb{Q}]$ ) of principal local units at  $p$  and its torsion subgroup, respectively; by class field theory this gives in the diagram:

$$\text{Gal}(H_K^{\text{pr}}/H_K) \simeq U_K/\overline{E}_K,$$

where  $\overline{E}_K$  is the closure of the group of  $p$ -principal global units of  $K$  (i.e., units  $\varepsilon \equiv 1 \pmod{\prod_{\mathfrak{p}|p} \mathfrak{p}}$ ):

$$\begin{array}{ccccc}
 & & \mathcal{T}_K = \text{tor}_{\mathbb{Z}_p}(\mathcal{G}_K^{\text{ab}}) & & \\
 & \text{---} & \text{---} & \text{---} & \\
 K_\infty & \xrightarrow{\#\mathcal{A}_K^\infty} & K_\infty H_K & \xrightarrow{\#\mathcal{R}_K \cdot \#\mathcal{W}_K} & H_K^{\text{pr}} \\
 | & & | & & | \\
 K_\infty \cap H_K & \xrightarrow{\quad} & H_K & \xrightarrow{\simeq U_K/\overline{E}_K} & H_K^{\text{pr}} \\
 | & & \curvearrowright \simeq \mathcal{A}_K & & | \\
 K & \xrightarrow{\quad} & & \xrightarrow{\mathcal{G}_K^{\text{ab}}} & F
 \end{array}$$

For any field  $k$ , let  $\mu_k$  be the group of roots of unity of  $k$  of  $p$ -power order. Then  $W_K = \bigoplus_{\mathfrak{p}|p} \mu_{K_{\mathfrak{p}}}$ . We have the following exact sequence defining  $\mathcal{W}_K$  and  $\mathcal{R}_K$  ([8, Lemma III.4.2.4] or [9, Lemma 3.1 & § 5]):

$$(2.2) \quad 1 \rightarrow \mathcal{W}_K := W_K/\mu_K \longrightarrow \text{tor}_{\mathbb{Z}_p}(U_K/\overline{E}_K) \\
 \xrightarrow{\log} \text{tor}_{\mathbb{Z}_p}(\log(U_K)/\log(\overline{E}_K)) =: \mathcal{R}_K \rightarrow 0.$$

The group  $\mathcal{R}_K$  is called the *normalized  $p$ -adic regulator of  $K$*  and makes sense for any number field (see the above references in [9] for more details and the main properties of these invariants).

It is clear that the annihilation of  $\mathcal{T}_K$  mainly concerns the group  $\mathcal{R}_K$  since the  $p$ -class group is in general trivial (and so for  $p$  large enough) and because the regulator may be non-trivial with large valuations and unpredictable  $p$  (see [11] for some conjectures and [10] giving programs of fast computation of the *group structure of  $\mathcal{T}_K$  for any number field* given by means of polynomials).

A field  $K$  is said to be  *$p$ -rational* if the Leopoldt conjecture is satisfied for  $p$  in  $K$  and if the torsion group  $\mathcal{T}_K$  is trivial. This has deep consequences in Galois theory since  $\mathcal{T}_K$  is the dual of  $H^2(\mathcal{G}_{K,S}, \mathbb{Z}_p(0))$  [17].

### 3. KUMMER THEORY AND SPIEGEL INVOLUTION

**3.1. Kummer theory.** We denote by  $\mathbb{Q}_n$ ,  $n \geq 0$ , the  $n$ th stage in  $\mathbb{Q}_\infty$  so that  $[\mathbb{Q}_n : \mathbb{Q}] = p^n$ . Let  $n_0 \geq 0$  be defined by  $K \cap \mathbb{Q}_\infty =: \mathbb{Q}_{n_0}$ .

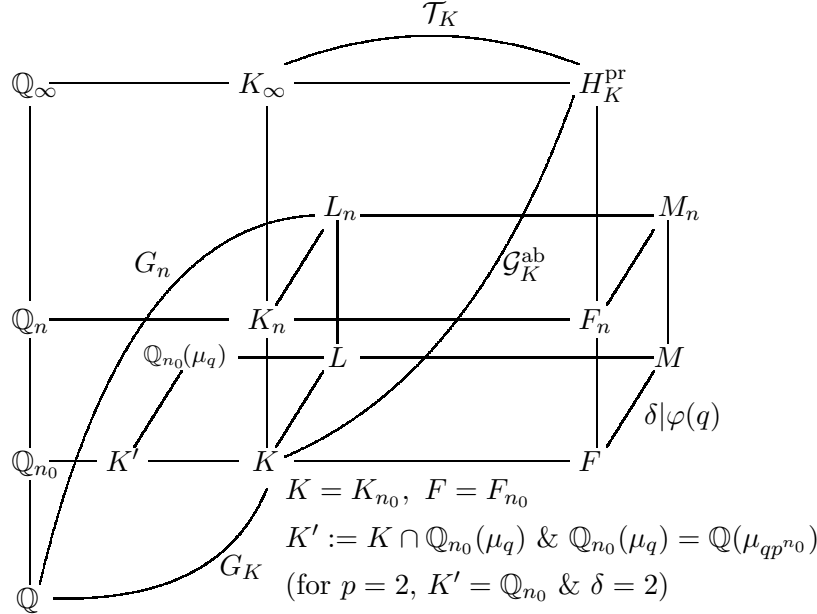
Let  $n \geq n_0$ . We denote by  $K_n$  the compositum  $K\mathbb{Q}_n$  and by  $F_n$  the compositum  $FK_n = F\mathbb{Q}_n$  (in other words,  $K = K_{n_0}$ ,  $F = F_{n_0}$ ). Then we have the *group isomorphism*  $\text{Gal}(F_n/K_n) \simeq \mathcal{T}_K$  for all  $n \geq n_0$ .

Put  $q = p$  (resp. 4) if  $p \neq 2$  (resp.  $p = 2$ ). Let  $L = K(\mu_q)$  and  $M = F(\mu_q)$ ; then put  $L_n := LK_n$  for all  $n \geq n_0$ .

Let  $M_n := F_n(\mu_q)$  (whence  $L = L_{n_0}$ ,  $M = M_{n_0}$ ). For  $p \neq 2$ , the degrees  $[L_n : K_n] = [M_n : F_n]$  are equal to a divisor  $\delta$  of  $p-1$  independent of  $n \geq n_0$  ( $\delta$  is even since  $K$  is real). For  $p = 2$ ,  $\delta = 2$ . In any case, one has, for  $n \geq n_0$ :

$$L_n = K(\mu_{qp^n}).$$

All this is summarized by the following diagram:



**Lemma 3.1.** *Let  $f_K$  be the conductor of  $K$ . Then the conductor  $f_{L_n}$  of  $L_n$  ( $n \geq n_0$ ) is equal to l.c.m.  $(f_K, qp^n)$ . Thus for  $n$  large enough (explicit),  $f_{L_n} = qp^n f'$ , with  $p \nmid f'$ .*

*Proof.* A classical formula (see, e.g., [8, Proposition II.4.1.1]).  $\square$

**Lemma 3.2.** *Let  $p^e$ ,  $e \geq 0$ , be the exponent of  $\mathcal{T}_K$ . Then, for all  $n \geq n_0 + e$ , the restriction  $\mathcal{T}_K \rightarrow \text{Gal}(F_n/K_n)$  is an isomorphism of  $G_K$ -modules.*

*Proof.* The abelian group  $\mathcal{G}_K^{\text{ab}} := \text{Gal}(H_K^{\text{Pr}}/K)$  is normal in  $\text{Gal}(H_K^{\text{Pr}}/\mathbb{Q})$ , then  $(\mathcal{G}_K^{\text{ab}})^{p^{n-n_0}}$  is normal; but  $(\mathcal{G}_K^{\text{ab}})^{p^{n-n_0}}$  fixes  $F_n$  which is Galois over  $\mathbb{Q}$ . In other words,  $G_K$ , as well as  $\text{Gal}(K_n/\mathbb{Q})$  or  $\text{Gal}(K_\infty/\mathbb{Q})$ , operate by conjugation in the same way since  $\mathcal{G}_K^{\text{ab}}$  is abelian; if  $F$  is clearly non-unique, then  $F_{n_0+e}$  is canonical, being the fixed field of  $(\mathcal{G}_K^{\text{ab}})^{p^e}$ .  $\square$

The use of the extension  $F$  is not strictly necessary but clarifies the reasoning which needs to work at any level  $n \geq n_0 + e$  to preserve Galois structures.

The extension  $M_n/L_n$  (of exponent  $p^e$ ) is a Kummer extension for the “exponent”  $qp^n$  since  $L_n$  contains the group  $\mu_{qp^n}$ , which is sufficient for  $n \geq n_0 + e$ .

Let  $G_n := \text{Gal}(L_n/\mathbb{Q})$  and let:

$$\text{Rad}_n := \{w \in L_n^\times, \sqrt[p^n]{w} \in M_n\}$$

be the radical of  $M_n/L_n$ . Then we have the group isomorphism:

$$\text{Rad}_n/L_n^{\times qp^n} \simeq \text{Gal}(M_n/L_n).$$

In some sense, the group  $\text{Rad}_n/L_n^{\times qp^n}$  does not depend on  $n \geq n_0 + e$  since the canonical isomorphism  $\text{Gal}(M_{n+h}/L_{n+h}) \simeq \text{Gal}(M_n/L_n)$  gives  $L_{n+h}(\sqrt[qp^n]{\overline{\text{Rad}_n}}) = M_{n+h}$ ; the map  $\text{Rad}_n/L_n^{\times qp^n} \xrightarrow{p^h} \text{Rad}_{n+h}/L_{n+h}^{\times qp^{n+h}}$  is an isomorphism for any  $h \geq 0$ . In other words, as soon as  $n \geq n_0 + e$ , we have:

$$\text{Rad}_n \subseteq L_n^{\times qp^{n-e}} \quad \& \quad \text{Rad}_{n+h} = \text{Rad}_n^{p^h} \cdot L_{n+h}^{\times qp^{n+h}}.$$

**3.2. Spiegel involution.** The structures of  $(\mathbb{Z}/qp^n\mathbb{Z})[G_n]$ -modules of the Galois group  $\text{Gal}(M_n/L_n)$  and  $\text{Rad}_n/L_n^{\times qp^n}$  are related via the ‘‘Spiegel involution’’ defined as follows: let  $\omega_n : G_n \rightarrow \mathbb{Z}/qp^n\mathbb{Z}$  be the *character of Teichmüller of level  $n$*  defined by:

$$\zeta^s = \zeta^{\omega_n(s)}, \quad \text{for all } s \in G_n \text{ and all } \zeta \in \mu_{qp^n}.$$

The Spiegel involution is the involution of  $(\mathbb{Z}/qp^n\mathbb{Z})[G_n]$  defined by:

$$x := \sum_{s \in G_n} a_s \cdot s \mapsto x^* := \sum_{s \in G_n} a_s \cdot \omega_n(s) \cdot s^{-1}.$$

Thus, if  $s$  is the Artin symbol  $\left(\frac{L_n}{a}\right)$ , then  $\left(\frac{L_n}{a}\right)^* \equiv a \cdot \left(\frac{L_n}{a}\right)^{-1} \pmod{qp^n}$ . For the convenience of the reader we prove once again the very classical:

**Lemma 3.3.** *Let  $n \geq n_0 + e$  where  $p^{n_0} = [K \cap \mathbb{Q}_\infty : \mathbb{Q}]$  and  $p^e$  is the exponent of  $\mathcal{T}_K$ . The annihilators  $A_n$  of  $\text{Gal}(M_n/L_n)$  (thus of  $\mathcal{T}_K$ ) in  $(\mathbb{Z}/qp^n\mathbb{Z})[G_n]$  are the images of the annihilators  $S_n$  of  $\text{Rad}_n/L_n^{\times qp^n}$  by the Spiegel involution and inversely. An annihilator  $A_n$  of  $\mathcal{T}_K$  only depends on its projection  $A_{K,n}$  in  $(\mathbb{Z}/qp^n\mathbb{Z})[G_K]$ .*

*Proof.* To simplify, put  $\overline{\text{Rad}} := \text{Rad}_n/L_n^{\times qp^n}$ ,  $\mathcal{T} := \text{Gal}(M_n/L_n) \simeq \mathcal{T}_K$ . Let:

$$\begin{aligned} \lambda : \overline{\text{Rad}} \times \mathcal{T} &\longrightarrow \mu_{qp^n} \\ (\overline{w}, \tau) &\longmapsto \left(\sqrt[qp^n]{\overline{w}}\right)^{\tau-1}; \end{aligned}$$

then  $\lambda$  is a non-degenerated  $\mathbb{Z}/qp^n\mathbb{Z}$ -bilinear form such that:

$$\lambda(\overline{w}^s, \tau) = \lambda(\overline{w}, \tau^{s^*}), \quad \text{for all } s \in G_n,$$

where  $s^* = \omega_n(s) \cdot s^{-1}$  (see e.g., [8, Corollary I.6.2.1]).

Let  $S_n = \sum_{s \in G_n} a_s \cdot s \in (\mathbb{Z}/qp^n\mathbb{Z})[G_n]$ ; then, for all  $(\overline{w}, \tau) \in \overline{\text{Rad}} \times \mathcal{T}$  we have:

$$\lambda(\overline{w}^{S_n}, \tau) = \prod_{s \in G_n} \lambda(\overline{w}^s, \tau)^{a_s} = \prod_{s \in G_n} \lambda(\overline{w}, \tau^{s^*})^{a_s} = \lambda(\overline{w}, \tau^{S_n^*}).$$

So, if  $S_n$  annihilates  $\overline{\text{Rad}}$ , then  $\lambda(\overline{w}, \tau^{S_n^*}) = 1$  for all  $\overline{w}$  &  $\tau$ ; since  $\lambda$  is non-degenerated,  $\tau^{S_n^*} = 1$  for all  $\tau \in \mathcal{T}$ . Whence the annihilation of  $\mathcal{T}$  by  $A_n = S_n^*$  (without any assumption on the Galois number field  $K$  nor on  $p$ ), then by the projection  $A_{K,n}$  since  $\text{Gal}(L_n/K)$  acts trivially on  $\text{Gal}(M_n/L_n)$ .  $\square$

*Remarks 3.4.* (i) As we have mention, the radical  $\text{Rad}_n$  does not depend really on the field  $L_n$ ; so, if we consider the radical of the maximal  $p$ -ramified abelian  $p$ -extension of  $L_n$ , of exponent  $qp^n$ :

$$\text{Rad}'_n := \{w' \in L_n^\times, L_n(\sqrt[qp^n]{w'})/L_n \text{ is } p\text{-ramified}\},$$

we obtain a group whose  $p$ -rank tends to infinity with  $n$ ; this is due mainly to the  $\mathbb{Z}_p$ -rank of the compositum of the  $\mathbb{Z}_p$ -extensions of  $L_n$  (totally imaginary) and from the less known  $\mathcal{T}_{L_n}$  which contains  $\mathcal{T}_{K,n}$ . But since  $\mathcal{T}_K$  is

annihilated by  $1 - s_\infty$ ,  $\text{Rad}_n/L_n^{\times qp^n}$  is annihilated by  $(1 - s_\infty)^* = 1 + s_\infty$  which means that only the “minus part” of  $\text{Rad}'_n/L_n^{\times qp^n}$  is needed, which eliminates the huge “plus” part containing in particular all the units. Thus  $\text{Rad}_n$  is essentially given by the “relative”  $S'$ -units of  $L_n$  ( $S'$  being the set of  $p$ -places of  $L_n$ ) and generators of some “relative”  $p$ -classes of  $L_n$ .

(ii) In the case  $p = 2$ , let  $\mathcal{T}_K^{\text{res}} := \text{tor}_{\mathbb{Z}_2}(\mathcal{G}_{K,S}^{\text{res ab}})$ , where  $\mathcal{G}_{K,S}^{\text{res}}$  is the Galois group of the maximal  $S$ -ramified (i.e., unramified outside  $2$  but possibly complexified) pro-2-extension  $H_K^{\text{pr res}}$  of  $K$  and let  $\text{Rad}_n^{\text{res}}$  the corresponding radical  $\{w \in L_n^\times, \sqrt[4 \cdot 2^n]{w} \in M_n^{\text{res}}\}$ , where  $M_n^{\text{res}}$  is analogous to  $M_n$  for the restricted sense. We observe that in the restricted sense, we have the exact sequence [8, Theorem III.4.1.5]  $0 \rightarrow (\mathbb{Z}/2\mathbb{Z})^d \rightarrow \mathcal{T}_K^{\text{res}} \rightarrow \mathcal{T}_K \rightarrow 1$ , then a dual exact sequence with radicals. As in [2], one may consider more general ray class fields and find results of annihilation with suitable Stickelberger or Solomon elements.

#### 4. STICKELBERGER ELEMENTS AND CYCLOTOMIC NUMBERS

**4.1. General definitions.** Let  $f \geq 1$  be any modulus and let  $\mathbb{Q}^f$  be the corresponding cyclotomic field  $\mathbb{Q}(\mu_f)$ .<sup>1</sup> Let  $L$  be a subfield of  $\mathbb{Q}^f$ .

(i) We define (where all Artin symbols are taken over  $\mathbb{Q}$ ):

$$\mathcal{S}_{\mathbb{Q}^f} := - \sum_{a=1}^f \left( \frac{a}{f} - \frac{1}{2} \right) \cdot \left( \frac{\mathbb{Q}^f}{a} \right)^{-1},$$

and the restriction  $\mathcal{S}_L := - \sum_{a=1}^f \left( \frac{a}{f} - \frac{1}{2} \right) \cdot \left( \frac{L}{a} \right)^{-1}$  to  $L$  of  $\mathcal{S}_{\mathbb{Q}^f}$ , where  $a$  runs through the integers  $a \in [1, f]$  prime to  $f$ . We know that the properties of annihilation of ideal classes need to multiply  $\mathcal{S}_L$  by an element of the ideal annihilator of the group  $\mu_f$  (or  $\mu_{2f}$ ), which is generated by  $f$  (or  $2f$ ) and the multipliers  $\delta_c := 1 - c \cdot \left( \frac{\mathbb{Q}^f}{c} \right)^{-1}$ , for  $c$  prime to  $2f$ . This shall give integral elements in the group algebra.

(ii) Then we define in the same way  $\eta_{\mathbb{Q}^f} := 1 - \zeta_f$  &  $\eta_L := N_{\mathbb{Q}^f/L}(1 - \zeta_f)$ , where  $\zeta_f$  is a primitive  $f$ th root of unity for which we assume the coherent definitions  $\zeta_f^d = \zeta_m$  if  $f = d \cdot m$ .

**Definition 4.1.** Since  $\frac{f-a}{f} - \frac{1}{2} = -\left(\frac{a}{f} - \frac{1}{2}\right)$  we have  $\mathcal{S}_{\mathbb{Q}^f} = \mathcal{S}'_{\mathbb{Q}^f} \cdot (1 - s_\infty)$  and  $\mathcal{S}_L = \mathcal{S}'_L \cdot (1 - s_\infty)$ , where  $s_\infty$  is the complex conjugation, and where:

$$\mathcal{S}'_{\mathbb{Q}^f} := - \sum_{a=1}^{f/2} \left( \frac{a}{f} - \frac{1}{2} \right) \cdot \left( \frac{\mathbb{Q}^f}{a} \right)^{-1} \quad \& \quad \mathcal{S}'_L := - \sum_{a=1}^{f/2} \left( \frac{a}{f} - \frac{1}{2} \right) \cdot \left( \frac{L}{a} \right)^{-1}.$$

**4.2. Norms of Stickelberger elements and cyclotomic numbers.** Let  $f \geq 1$  and  $m \mid f$  be any modulus and let  $\mathbb{Q}^f$  and  $\mathbb{Q}^m \subseteq \mathbb{Q}^f$  be the corresponding cyclotomic fields. Let  $N_{\mathbb{Q}^f/\mathbb{Q}^m}$  be the restriction map:

$$\mathbb{Q}[\text{Gal}(\mathbb{Q}^f/\mathbb{Q})] \longrightarrow \mathbb{Q}[\text{Gal}(\mathbb{Q}^m/\mathbb{Q})],$$

<sup>1</sup>Such modulus are conductors of the corresponding cyclotomic fields, except for an even integer not divisible by 4; but this point of view is essential to establish the functional properties of Stickelberger elements and cyclotomic numbers. So, if  $f$  is odd, we distinguish, by abuse, the notations  $\mathbb{Q}^f$  and  $\mathbb{Q}^{2f}$ .

or the usual arithmetic norm in  $\mathbb{Q}^f/\mathbb{Q}^m$ . Consider as above:

$$\mathcal{S}_{\mathbb{Q}^f} := - \sum_{a=1}^f \left( \frac{a}{f} - \frac{1}{2} \right) \cdot \left( \frac{\mathbb{Q}^f}{a} \right)^{-1} \quad \& \quad \eta_{\mathbb{Q}^f} := 1 - \zeta_f.$$

We have, respectively:

$$(4.1) \quad N_{\mathbb{Q}^f/\mathbb{Q}^m}(\mathcal{S}_{\mathbb{Q}^f}) = \prod_{\ell|f, \ell \nmid m} \left( 1 - \left( \frac{\mathbb{Q}^m}{\ell} \right)^{-1} \right) \cdot \mathcal{S}_{\mathbb{Q}^f},$$

$$(4.2) \quad N_{\mathbb{Q}^f/\mathbb{Q}^m}(\eta_{\mathbb{Q}^f}) = (\eta_{\mathbb{Q}^m})^{\prod_{\ell|f, \ell \nmid m} \left( 1 - \left( \frac{\mathbb{Q}^m}{\ell} \right)^{-1} \right)}.$$

As we have explained in the previous footnote, if  $m$  is odd, then we have:

$$N_{\mathbb{Q}^{2m}/\mathbb{Q}^m}(\mathcal{S}_{\mathbb{Q}^{2m}}) = \left( 1 - \left( \frac{\mathbb{Q}^m}{2} \right)^{-1} \right) \cdot \mathcal{S}_{\mathbb{Q}^m}, \quad N_{\mathbb{Q}^{2m}/\mathbb{Q}^m}(\eta_{\mathbb{Q}^{2m}}) = \eta_{\mathbb{Q}^m}^{\left( 1 - \left( \frac{\mathbb{Q}^m}{2} \right)^{-1} \right)},$$

where the “norms”  $N_{\mathbb{Q}^{2m}/\mathbb{Q}^m}$  are of course the identity. For instance one verifies immediately that  $\mathcal{S}_{\mathbb{Q}^6} = \frac{1}{3}(1 - s_\infty)$  and  $\mathcal{S}_{\mathbb{Q}^3} = \frac{1}{6}(1 - s_\infty)$ , but since 2 is inert in  $\mathbb{Q}^3/\mathbb{Q}$ ,  $\left( 1 - \left( \frac{\mathbb{Q}^3}{2} \right)^{-1} \right) = 1 - s_\infty$  and one must compute  $(1 - s_\infty)\mathcal{S}_{\mathbb{Q}^3} = \frac{1}{6}(1 - s_\infty)^2 = \frac{1}{3}(1 - s_\infty)$  as expected.

If  $L$  (imaginary or real), of conductor  $f$ , is an extension of  $k$ , of conductor  $m \mid f$ , let  $\mathcal{S}_L := N_{\mathbb{Q}^f/L}(\mathcal{S}_{\mathbb{Q}^f})$  and  $\eta_L := N_{\mathbb{Q}^f/L}(\eta_{\mathbb{Q}^f})$ , then:

$$N_{L/k}(\mathcal{S}_L) = \prod_{\ell|f, \ell \nmid m} \left( 1 - \left( \frac{k}{\ell} \right)^{-1} \right) \cdot \mathcal{S}_k,$$

$$N_{L/k}(\mathcal{S}'_L) \equiv \prod_{\ell|f, \ell \nmid m} \left( 1 - \left( \frac{k}{\ell} \right)^{-1} \right) \cdot \mathcal{S}'_k \pmod{(1 + s_\infty) \cdot \mathbb{Q}[G_k]},$$

$$N_{L/k}(\eta_L) = (\eta_k)^{\prod_{\ell|f, \ell \nmid m} \left( 1 - \left( \frac{k}{\ell} \right)^{-1} \right)}.$$

This implies that  $N_{L/k}(\mathcal{S}_L) = 0$  (resp.  $N_{L/k}(\eta_L) = 1$ ) as soon as the prime  $\ell$  totally splits in  $k$ . In particular, if  $k$  is real, the formula is valid for the infinite place and  $N_{L/k}(\mathcal{S}_L) = 0$  (of course, if  $L$  is real,  $\mathcal{S}_L = 0$ ).

For the classical proofs, we consider by induction the case  $f = \ell \cdot m$ , with  $\ell$  prime and examine the two cases  $\ell \mid m$  and  $\ell \nmid m$ ; for the case of cyclotomic numbers, see [29, § 8.1]; the case of Stickelberger elements been crucial for our purpose, we give again a proof (a similar reasoning will be detailed for the Theorem 7.2). To simplify, put  $\mathcal{S}_{\mathbb{Q}^f} =: \mathcal{S}_f$ ,  $\mathcal{S}_{\mathbb{Q}^m} =: \mathcal{S}_m$ , and consider  $\mathcal{S}_f = - \sum_{a=1}^f \left( \frac{a}{f} - \frac{1}{2} \right) \cdot \left( \frac{\mathbb{Q}^f}{a} \right)^{-1}$ , for  $f = \ell \cdot m$ ,  $\ell \nmid m$ , where  $a$  runs through the integers  $a \in [1, f]$  prime to  $f$ . Put  $a = b + \lambda \cdot m$ ,  $b \in [1, m]$ ,  $\lambda \in [0, \ell - 1]$ ; since  $a$  must be prime to  $f$ ,  $b$  is automatically prime to  $m$  but we must exclude  $\lambda_b^* \in [0, \ell - 1]$  such that:

$$b + \lambda_b^* \cdot m = b'_\ell \cdot \ell, \quad b'_\ell \in [1, m] \quad (b'_\ell \text{ is necessarily prime to } m).$$

We then have:

$$\begin{aligned} & N_{\mathbb{Q}^f/\mathbb{Q}^m}(\mathcal{S}_f) \\ &= - \sum_{a=1}^f \left( \frac{a}{f} - \frac{1}{2} \right) \cdot \left( \frac{\mathbb{Q}^m}{a} \right)^{-1} = - \sum_{b, \lambda \neq \lambda_b^*} \left( \frac{b + \lambda m}{\ell m} - \frac{1}{2} \right) \cdot \left( \frac{\mathbb{Q}^m}{b} \right)^{-1} \end{aligned}$$

$$\begin{aligned}
&= -\sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \sum_{\lambda \neq \lambda_b^*} \left(\frac{b}{\ell m} + \frac{\lambda}{\ell} - \frac{1}{2}\right) \\
&= -\sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \left(\frac{\ell-1}{\ell} \frac{b}{m} - \frac{\ell-1}{2}\right) - \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \frac{1}{\ell} \left(\frac{\ell(\ell-1)}{2} - \lambda_b^*\right) \\
&= -\left(1 - \frac{1}{\ell}\right) \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \frac{b}{m} + \frac{1}{\ell} \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \lambda_b^*.
\end{aligned}$$

Since the correspondence  $b \mapsto b'_\ell$  is bijective on the set of elements prime to  $m$  in  $[1, m]$ , one has, with  $\lambda_b^* = \frac{b'_\ell \cdot \ell - b}{m}$  and  $\left(\frac{\mathbb{Q}^m}{b}\right) = \left(\frac{\mathbb{Q}^m}{b'_\ell}\right) \left(\frac{\mathbb{Q}^m}{\ell}\right)$ :

$$\begin{aligned}
\frac{1}{\ell} \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \lambda_b^* &= \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \frac{b'_\ell}{m} - \frac{1}{\ell} \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \frac{b}{m} \\
&= \left(\frac{\mathbb{Q}^m}{\ell}\right)^{-1} \sum_b \left(\frac{\mathbb{Q}^m}{b'_\ell}\right)^{-1} \frac{b'_\ell}{m} - \frac{1}{\ell} \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \frac{b}{m} \\
&= \left(\left(\frac{\mathbb{Q}^m}{\ell}\right)^{-1} - \frac{1}{\ell}\right) \cdot \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \frac{b}{m}.
\end{aligned}$$

Thus we obtain:

$$\begin{aligned}
N_{\mathbb{Q}^f/\mathbb{Q}^m}(\mathcal{S}_f) &= -\left(1 - \frac{1}{\ell}\right) \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \frac{b}{m} + \left(\left(\frac{\mathbb{Q}^m}{\ell}\right)^{-1} - \frac{1}{\ell}\right) \cdot \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \frac{b}{m} \\
&= -\left(1 - \left(\frac{\mathbb{Q}^m}{\ell}\right)^{-1}\right) \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \frac{b}{m}.
\end{aligned}$$

But  $\frac{1}{2} \sum_b \left(\frac{\mathbb{Q}^m}{b}\right)^{-1} \left(1 - \left(\frac{\mathbb{Q}^m}{\ell}\right)^{-1}\right) = 0$ ; so replacing  $\frac{b}{m}$  by  $\frac{b}{m} - \frac{1}{2}$  we get:

$$N_{\mathbb{Q}^f/\mathbb{Q}^m}(\mathcal{S}_f) = \left(1 - \left(\frac{\mathbb{Q}^m}{\ell}\right)^{-1}\right) \cdot \mathcal{S}_m.$$

Then it is easy to compute that if  $\ell \mid m$ , any  $\lambda \in [0, \ell - 1]$  is suitable, giving:

$$N_{\mathbb{Q}^f/\mathbb{Q}^m}(\mathcal{S}_f) = \mathcal{S}_m.$$

**4.3. Multiplicators of Stickelberger elements  $\mathcal{S}_{L_n}$ .** The conductor of  $L_n$  is  $f_{L_n} = \text{l.c.m.}(f_K, qp^n)$  (Lemma 3.1). So in general  $f_{L_n} = qp^n \cdot f'$  with  $p \nmid f'$ , except if  $f_K$  is divisible by a large power of  $p$  in which case one must take  $n$  large enough in the practical computations. In some formulas we shall abbreviate  $f_{L_n}$  by  $f_n$ .

Let  $c$  be an (odd) integer, prime to  $f_n$ , and let:

$$(4.3) \quad \mathcal{S}_{L_n}(c) := \left(1 - c \left(\frac{L_n}{c}\right)^{-1}\right) \cdot \mathcal{S}_{L_n}.$$

Then  $\mathcal{S}_{L_n}(c) \in \mathbb{Z}[G_n]$  as we have explain; indeed, we have:

$$\mathcal{S}_{L_n}(c) = \frac{-1}{f_n} \sum_a \left[ a \left(\frac{L_n}{a}\right)^{-1} - ac \left(\frac{L_n}{a}\right)^{-1} \left(\frac{L_n}{c}\right)^{-1} \right] + \frac{1-c}{2} \sum_a \left(\frac{L_n}{a}\right)^{-1}.$$

Let  $a'_c \in [1, f_n]$  be the unique integer such that  $a'_c \cdot c \equiv a \pmod{f_n}$  and put  $a'_c \cdot c = a + \lambda_a^n(c) f_n$ ,  $\lambda_a^n(c) \in \mathbb{Z}$ ; then, using the bijection  $a \mapsto a'_c$  in the second summation and the fact that  $\left(\frac{L_n}{a'_c}\right) \left(\frac{L_n}{c}\right) = \left(\frac{L_n}{a}\right)$ , this yields:



$$\begin{aligned}
\mathcal{S}_{L_n}(c) &= \frac{-1}{f_n} \left[ \sum_a a \left(\frac{L_n}{a}\right)^{-1} - \sum_a a'_c \cdot c \left(\frac{L_n}{a'_c}\right)^{-1} \left(\frac{L_n}{c}\right)^{-1} \right] \\
&\quad + \frac{1-c}{2} \sum_a \left(\frac{L_n}{a}\right)^{-1} \\
(4.4) \quad &= \frac{-1}{f_n} \sum_a \left[ a - a'_c \cdot c \right] \left(\frac{L_n}{a}\right)^{-1} + \frac{1-c}{2} \sum_a \left(\frac{L_n}{a}\right)^{-1} \\
&= \sum_a \left[ \lambda_a^n(c) + \frac{1-c}{2} \right] \left(\frac{L_n}{a}\right)^{-1} \in \mathbb{Z}[G_n].
\end{aligned}$$

**Lemma 4.2.** *We have the relations  $\lambda_{f_n-a}^n(c) + \frac{1-c}{2} = -(\lambda_a^n(c) + \frac{1-c}{2})$  for all  $a \in [1, f_n]$  prime to  $f_n$ . Then  $\mathcal{S}'_{L_n}(c) := \sum_{a=1}^{f_n/2} \left[ \lambda_a^n(c) + \frac{1-c}{2} \right] \left(\frac{L_n}{a}\right)^{-1} \in \mathbb{Z}[G_n]$  is such that  $\mathcal{S}_{L_n}(c) = \mathcal{S}'_{L_n}(c) \cdot (1 - s_\infty)$ , whence  $\mathcal{S}_{L_n}(c)^* = \mathcal{S}'_{L_n}(c)^* \cdot (1 + s_\infty)$ .*

*Proof.* By definition, the integer  $(f_n - a)'_c$  is in  $[1, f_n]$  and congruent modulo  $f_n$  to  $(f_n - a) c^{-1} \equiv -ac^{-1} \equiv -a'_c \pmod{f_n}$ ; thus  $(f_n - a)'_c = f_n - a'_c$  and

$$\lambda_{f_n-a}^n(c) = \frac{(f_n - a)'_c c - (f_n - a)}{f_n} = \frac{(f_n - a'_c) c - (f_n - a)}{f_n} = c - 1 - \lambda_a^n(c),$$

whence  $\lambda_{f_n-a}^n(c) + \frac{1-c}{2} = -(\lambda_a^n(c) + \frac{1-c}{2})$  and the result.  $\square$

The multiplier  $\delta_c := (1 - c \left(\frac{L_n}{c}\right)^{-1})$  has a great importance since the image of  $\delta_c$  by the Spiegel involution is  $\delta_c^* := 1 - \left(\frac{L_n}{c}\right) \pmod{qp^n}$ ; the order of the Artin symbol of  $c$  shall be crucial.

## 5. ANNIHILATIONS OF RADICALS AND GALOIS GROUPS

**5.1. Annihilation of  $\text{Rad}_n/L_n^{\times qp^n}$ .** We begin with the classical property of annihilation of class groups of imaginary abelian fields by modified Stickelberger elements  $\mathcal{S}_{L_n}(c) := \delta_c \cdot \mathcal{S}_{L_n}$ . Before let's give two technical lemmas. Recall that  $\mathcal{S}_{L_n}(c) =: \mathcal{S}'_{L_n}(c) \cdot (1 - s_\infty)$  and that, from § 4.2, the  $\mathcal{S}_{L_n}$ ,  $\mathcal{S}_{L_n}(c)$  and  $\mathcal{S}'_{L_n}(c) \pmod{(1 + s_\infty)\mathbb{Z}[G_n]}$  form coherent families in  $\varprojlim_{n \geq n_0+e} \mathbb{Q}[G_n]$  for the “norm”.

**Lemma 5.1.** *Let  $\zeta \in \mu_{qp^n}$ ,  $n \geq n_0 + e$ . If  $\zeta \in \text{Rad}_n$  (or  $\text{Rad}_n^{\text{res}}$  when  $p = 2$ ) then  $\zeta = 1$ .*

*Proof.* If  $\zeta \neq 1$  with  $L_n(\sqrt[qp^n]{\zeta}) \subseteq M_n$  (or  $M_n^{\text{res}}$ ), we would have  $L_n(\sqrt[qp^n]{\zeta}) = L_{n+h}$ , where  $h \geq 1$  since  $\sqrt[qp^n]{\zeta}$  is of order  $\geq qp^{n+1}$  and since  $\mu_{p^\infty} \cap L_n^\times = \mu_{qp^n}$ , which is absurd because of the linear disjunction  $L_{n+h} \cap M_n = L_n$  (or  $L_{n+h} \cap M_n^{\text{res}} = L_n$ ).  $\square$

**Lemma 5.2.** *Let  $w_0 \in \text{Rad}_n$  be a real number. Then  $w_0^2 \in L_n^{\times qp^n}$ .*

*Proof.* Since  $K$  is real, we know that  $1 - s_\infty$  annihilates the  $(\mathbb{Z}/qp^n\mathbb{Z})[G_n]$ -module  $\text{Gal}(M_n/L_n)$ , thus  $1 + s_\infty$  annihilates  $\text{Rad}_n/L_n^{\times qp^n}$  and  $w_0^{1+s_\infty} = w_0^2 \in L_n^{\times qp^n}$  (this does not work for the restricted sense since the minus part of  $\mathcal{T}_K^{\text{res}}$  is of order  $2^d$ ).  $\square$

**Theorem 5.3.** *Let  $p^e$  be the exponent of  $\mathcal{T}_K := \text{tor}_{\mathbb{Z}_p}(\mathcal{G}_{K,S}^{\text{ab}})$  ( $p$ -ramification in the ordinary sense). For  $p = 2$ , let  $2^{e^{\text{res}}}$  be the exponent of  $\mathcal{T}_K^{\text{res}} := \text{tor}_{\mathbb{Z}_2}(\mathcal{G}_{K,S}^{\text{res ab}})$ , where  $\mathcal{G}_{K,S}^{\text{res}}$  is the Galois group of the maximal  $S$ -ramified in the restricted sense (i.e., unramified outside 2) pro-2-extension of  $K$  and let  $\text{Rad}_n^{\text{res}}$  be the corresponding radical.*

(i)  $p > 2$ . For all  $n \geq n_0 + e$ , the  $(\mathbb{Z}/qp^n\mathbb{Z})[G_n]$ -module  $\text{Rad}_n/L_n^{\times qp^n}$  is annihilated by  $\mathcal{S}'_{L_n}(c)$ . Thus,  $\mathcal{S}'_{L_n}(c)^*$  annihilates  $\mathcal{T}_K$ .

(ii)  $p = 2$ , ordinary sense. The annihilation occurs with  $2\mathcal{S}_{L_n}(c)$  and with  $4\mathcal{S}'_{L_n}(c)$ . Thus  $2\mathcal{S}_{L_n}(c)^*$  and  $4\mathcal{S}'_{L_n}(c)^*$  annihilate  $\mathcal{T}_K$ .

(iii)  $p = 2$ , restricted sense. For all  $n \geq n_0 + e^{\text{res}}$ , the  $(\mathbb{Z}/4 \cdot 2^n\mathbb{Z})[G_n]$ -module  $\text{Rad}_n^{\text{res}}/L_n^{\times 4 \cdot 2^n}$  is annihilated by  $2\mathcal{S}_{L_n}(c)$ ; thus  $2\mathcal{S}_{L_n}(c)^*$  annihilates  $\mathcal{T}_K^{\text{res}}$ .

*Proof.* Let  $w \in \text{Rad}_n$ ; since  $L_n(\sqrt[qp^n]{w})/L_n$  is  $p$ -ramified,  $(w) = \mathfrak{a}^{qp^n} \cdot \mathfrak{b}$  where  $\mathfrak{a}$  is an ideal of  $L_n$ , prime to  $p$ , and  $\mathfrak{b}$  is a product of prime ideals  $\mathfrak{p}_n$  of  $L_n$  dividing  $p$ . Let  $\mathfrak{p}_n \mid \mathfrak{b}$  and consider  $\mathfrak{p}_n^{\mathcal{S}_{L_n}(c)}$ ; one can replace  $\mathcal{S}_{L_n}(c)$  by its restriction to the decomposition field  $k$  (possibly  $k = \mathbb{Q}$ ) of  $p$  in the abelian extension  $L_n/\mathbb{Q}$ , which gives rise to the Euler factor  $1 - \left(\frac{k}{p}\right)^{-1}$  since  $k$ , of conductor prime to  $p$ , is strictly contained in  $L_n$  for  $n \geq n_0 + e$ ; so this factor is 0 and  $\mathfrak{b}^{\mathcal{S}_{L_n}(c)} = 1$ .

From the principality of the ideal  $\mathfrak{a}^{\mathcal{S}_{L_n}(c)}$  (Stickelberger's theorem) there exists  $\alpha_n \in L_n^{\times}$  and a unit  $\varepsilon_n$  of  $L_n$  such that:

$$(5.1) \quad w^{\mathcal{S}_{L_n}(c)} = \alpha_n^{qp^n} \cdot \varepsilon_n.$$

We see that  $\varepsilon_n^{1+s_\infty}$  is the  $qp^n$ th power of a unit of  $L_n$ : consider  $\varepsilon_n^{1+s_\infty}$  in (5.1) with the fact that  $\mathcal{S}_{L_n}(c) = \mathcal{S}'_{L_n}(c)(1 - s_\infty)$ . Since the  $\mathbb{Z}$ -rank of the groups of units of  $L_n$  and  $L_n^+$  (the maximal real subfield of  $L_n$ ) are equal, a power  $\varepsilon_n^N$  of  $\varepsilon_n$  is a real unit; so  $\varepsilon_n^{1-s_\infty}$  is a torsion element and  $\varepsilon_n^2 = \varepsilon_n^{1+s_\infty} \varepsilon_n^{1-s_\infty}$  is equal, up to a  $qp^n$ th power, to a  $p$ -torsion element of the form  $\zeta' \in \text{Rad}_n$ . Thus  $\zeta' = 1$  (Lemma 5.1) and  $\varepsilon_n^2 \in L_n^{\times qp^n}$ .

(i) Case  $p \neq 2$ . We deduce from the above that  $\varepsilon_n \in L_n^{\times p^{n+1}}$ . We have  $w^{\mathcal{S}'_{L_n}(c)(1-s_\infty)} = \beta_n^{p^{n+1}}$ ; but  $\beta_n^{1+s_\infty} = 1$  (the property is also true for  $p = 2$  since the result is a totally positive root of unity in  $L_n^+$ , but the proof only works taking the square of the relation (5.1) using  $\varepsilon_n^2$ ), and there exists  $\gamma_n \in L_n^{\times}$  such that  $\beta_n = \gamma_n^{1-s_\infty}$ , and  $w^{\mathcal{S}'_{L_n}(c)} \cdot \gamma_n^{-p^{n+1}} = w_0$ , a real number in the radical, thus a  $p^{n+1}$ th power (Lemma 5.2) (as above, the proof for  $p = 2$  only works taking once again the square of this relation to get  $w_0^2$ ). Other proof for any  $p \geq 2$ : since  $\mathcal{T}_K$  is annihilated by  $1 - s_\infty$ ,  $\text{Rad}_n/L_n^{\times qp^n}$  is annihilated by  $1 + s_\infty$ , thus  $w^{1-s_\infty} \in w^2 \cdot L_n^{\times qp^n}$  for all  $w \in \text{Rad}_n$ , and  $w^{\mathcal{S}_{L_n}(c)} = w^2 \mathcal{S}'_{L_n}(c)$  up to  $L_n^{\times qp^n}$ .

(ii) Case  $p = 2$  in the ordinary sense (so  $L_n^+ = K_n$ ). The result is obvious taking the square in the previous computations giving  $\varepsilon_n^2$  instead of  $\varepsilon_n$  for the annihilation with  $2\mathcal{S}_{L_n}(c)$ , then  $w_0^2$  for the annihilation with  $4\mathcal{S}'_{L_n}(c)$ .

(iii) Case  $p = 2$  in the restricted sense. The proof is in fact contained in the same relation  $(w) = \mathfrak{a}^{4 \cdot 2^n} \cdot \mathfrak{b}$ , for all  $w \in \text{Rad}_n^{\text{res}}$ , where  $\mathfrak{a}$  is an ideal of  $L_n$ , prime to 2, and  $\mathfrak{b}$  is a product of prime ideals  $\mathfrak{p}_n$  of  $L_n$  dividing 2, then the relation (5.1),  $n \geq n_0 + e$ .  $\square$

**5.2. Computation of  $\mathcal{S}_{L_n}(c)^*$  or  $\mathcal{S}'_{L_n}(c)^*$  and annihilation of  $\mathcal{T}_K$ .** From the expressions (4.3), (4.4) of  $\mathcal{S}_{L_n}(c)$ , the image by the Spiegel involution is:

$$\mathcal{S}_{L_n}(c)^* \equiv \sum_a \left[ \lambda_a^n(c) + \frac{1-c}{2} \right] a^{-1} \left( \frac{L_n}{a} \right) \pmod{qp^n},$$

which defines a coherent family  $(\mathcal{S}_{L_n}(c)^*)_n \in \varprojlim_{n \geq n_0+e} \mathbb{Z}/qp^n \mathbb{Z}[G_n]$  of annihilators of the Galois groups  $\text{Gal}(M_n/L_n) \simeq \mathcal{T}_K$ .

In the case  $p \neq 2$ , one may use equivalently  $\mathcal{S}'_{L_n}(c)^*$  with the half summation. Since the operation of  $\text{Gal}(L_n/K)$  on  $\text{Gal}(M_n/L_n)$  is trivial (see Lemma 3.3), by restriction of  $\mathcal{S}_{L_n}(c)^*$  to  $K$  one obtains a coherent family of annihilators of  $\mathcal{T}_K$  denoted  $(\mathcal{A}_{K,n}(c))_n \in \varprojlim_{n \geq n_0+e} \mathbb{Z}/qp^n \mathbb{Z}[G_K]$ , whose limit:

$$\mathcal{A}_K(c) := \lim_{n \rightarrow \infty} \mathcal{A}_{K,n}(c) = \lim_{n \rightarrow \infty} \sum_a \left[ \lambda_a^n(c) + \frac{1-c}{2} \right] a^{-1} \left( \frac{K}{a} \right) \in \mathbb{Z}_p[G_K]$$

is a canonical annihilator of  $\mathcal{T}_K$  that we shall link to  $p$ -adic  $L$ -functions; of course, it is sufficient to know its coefficients modulo the exponent  $p^e$  of  $\mathcal{T}_K$  and in a programming point of view, the element  $\mathcal{A}_{K,n_0+e}(c)$  annihilates  $\mathcal{T}_K$ , knowing that [10, Program I, § 3.2] gives the group structure of  $\mathcal{T}_K$ .

*Remark 5.4.* Let  $\alpha_{L_n} := \sum_{a=1}^{f_n} a^{-1} \left( \frac{L_n}{a} \right) = \left[ \sum_{a=1}^{f_n} \left( \frac{L_n}{a} \right)^{-1} \right]^*$ ; we have:

$$\alpha_{L_n} := \sum_{a=1}^{f_n/2} a^{-1} \left( \frac{L_n}{a} \right) + (f_n - a)^{-1} \left( \frac{L_n}{f_n - a} \right) \equiv \sum_{a=1}^{f_n/2} a^{-1} \left( \frac{L_n}{a} \right) (1 - s_\infty) \pmod{f_n}$$

which annihilates  $\mathcal{T}_K$  and is such that  $N_{L_n/K}(\alpha_{L_n}) \equiv 0 \pmod{qp^n}$ . We shall neglect such expressions and use the symbol  $\cong$ , where  $A \cong B \pmod{p^{n+1}}$

will mean  $A = B + \mu \cdot p^{n+1} + \nu \cdot \sum_{a=1}^{f_n} a^{-1} \left( \frac{K}{a} \right)$ , in the group algebra  $\mathbb{Z}_p[G_K]$ ,  $\mu, \nu$  in  $\mathbb{Z}_p$  (we put the modulus  $p^{n+1}$  instead of  $qp^n$  to cover, subsequently, the case  $p = 2$ ; moreover,  $p^{n+1}$  annihilates  $\mathcal{T}_K$  since  $n \geq n_0 + e$ ).

Thus, we have obtained:

**Theorem 5.5.** *Let  $c$  be any integer prime to  $2p$  and to the conductor of  $K$ . Assume  $n \geq n_0 + e$  and let  $f_n$  be the conductor of  $L_n$ ; for all  $a \in [1, f_n]$ , prime to  $f_n$ , let  $a'_c$  be the unique integer in  $[1, f_n]$  such that  $a'_c \cdot c \equiv a \pmod{f_n}$  and put  $a'_c \cdot c - a = \lambda_a^n(c) f_n$ ,  $\lambda_a^n(c) \in \mathbb{Z}$ . Let  $\mathcal{A}_{K,n}(c) := \sum_{a=1}^{f_n} \lambda_a^n(c) a^{-1} \left( \frac{K}{a} \right)$  and put  $\mathcal{A}_{K,n}(c) = \mathcal{A}'_{K,n}(c) \cdot (1 + s_\infty)$  where  $\mathcal{A}'_{K,n}(c) = \sum_{a=1}^{f_n/2} \lambda_a^n(c) a^{-1} \left( \frac{K}{a} \right)$ .*

*Let  $\mathcal{A}_K(c) := \lim_{n \rightarrow \infty} \left[ \sum_{a=1}^{f_n} \lambda_a^n(c) a^{-1} \left( \frac{K}{a} \right) \right]$  and  $\mathcal{A}_K(c) =: \mathcal{A}'_K(c) \cdot (1 + s_\infty)$ .*

*(i) For  $p \neq 2$ ,  $\mathcal{A}'_K(c)$  annihilates the  $\mathbb{Z}_p[G_K]$ -module  $\mathcal{T}_K$ .*

*(ii) For  $p = 2$ , the annihilation is true for  $2 \cdot \mathcal{A}_K(c)$  or  $4 \cdot \mathcal{A}'_K(c)$ .*

In practice, when the exponent  $p^e$  is known, one can use  $n = n_0 + e$  and the annihilators  $\mathcal{A}_{K,n}(c)$  or  $\mathcal{A}'_{K,n}(c)$ , the annihilator limit  $\mathcal{A}_K(c)$  being related to  $p$ -adic  $L$ -functions, then to elements like those of Solomon, thus giving the other approach that we have obtained in Theorem 9.4.

*Remark 5.6.* We have proved in a seminar report (1977) that for  $p = 2$ ,  $\mathcal{S}'_{L_n}(c)$  annihilates  $\mathcal{C}_{L_n}/\mathcal{C}_{L_n}^0$ , where  $\mathcal{C}_{L_n}$  is the 2-class group of  $L_n$  and where  $\mathcal{C}_{L_n}^0$  is generated by the classes of the *the invariant ideals* in  $L_n/K_n$ .

This shows that some 2-classes may give an obstruction; but  $\text{Rad}_n$  is particular as we have explained in Remark 3.4. In [14], C. Greither gives suitable statements about Stickelberger's theorem for  $p = 2$ , using the main theorems of Iwasawa's theory about the orders  $\frac{1}{2}L_2(1, \chi)$  of the isotypic components.

From this, as well as some numerical experiments and the roles of  $\varepsilon_n$  and  $w_0$  in the above reasonings, we may propose the following conjecture:

**Conjecture 5.7.** *Let  $p = 2$  and let  $K$  be a real abelian number field not contained in the cyclotomic  $\mathbb{Z}_2$ -extension.*

*Put  $\mathcal{A}_K(c) = \mathcal{A}'_K(c) \cdot (1 + s_\infty)$ . Then  $\mathcal{A}'_K(c)$  annihilates  $\mathcal{T}_K$ .*

If there exists, in the class of  $\mathcal{A}'_K(c)$  modulo the norm  $\sum_{\sigma \in G_K} \sigma$ , an element of the form  $2 \cdot \mathcal{A}''_K(c)$ ,  $\mathcal{A}''_K(c)$ , one may ask if  $\mathcal{A}''_K(c)$  does annihilate  $\mathcal{T}_K$ .

We shall give a counterexample for the annihilation of  $\mathcal{T}_K$  by  $\mathcal{A}''_K(c)$  (see § 6.6), but we ignore if this may be true under some assumptions.

**5.3. Cyclic cubic fields with  $p \equiv 1 \pmod{3}$ .** To simplify we suppose  $f_K$  prime. The first part of the program gives a defining polynomial. A second part computes the  $p$ -adic valuation of  $\#\mathcal{T}_K$  (in *vptor*) using [10, Program I, § 3.2] and gives  $\mathcal{A}_K(c) = \Lambda_0 + \Lambda_1\sigma^{-1} + \Lambda_2\sigma^{-2}$  modulo a power of  $p$ , after the choice of  $c$ , prime to  $2pf_K$ , with an Artin symbol of order 3:

```
{p=7;nt=8;forprime(f=7,10^4,if(Mod(f,3)!=1,next);
for(bb=1,sqrt(4*f/27),if(vf==2 & Mod(bb,3)==0,next);A=4*f-27*bb^2;
if(issquare(A,&aa)==1,if(Mod(aa,3)==1,aa=-aa);
P=x^3+x^2+(1-f)/3*x+(f*(aa-3)+1)/27;K=bnfinit(P,1);Kpn=bnrinit(K,p^nt);
C5=component(Kpn,5);Hpn0=component(C5,1);Hpn=component(C5,2);
h=component(component(component(K,8),1),2);L=listcreate;ex=0;
i=component(matsize(Hpn),2);R=0;for(k=1,i-1,co=component(Hpn,i-k+1);
if(Mod(co,p)==0,R=R+1;val=valuation(co,p);if(val>ex,ex=val);
listinsert(L,p^val,1));Hpn1=component(Hpn,1);
vptor=valuation(Hpn0/Hpn1,p);if(vptor>1,S0=0;S1=0;S2=0;
pN=p*p^ex;nu=(f-1)/3;fn=pN*f;z=znprimroot(f);
zz=lift(z);t=lift(Mod((1-zz)/f,2*p));c=zz+t*f;
for(a=1,fn/2,if(gcd(a,fn)!=1,next);asurc=lift(a*Mod(c,fn)^-1);
lambda=(asurc*c-a)/fn;u=Mod(lambda*a^-1,pN);
a0=lift((a*z^0)^nu);a1=lift((a*z^2)^nu);a2=lift((a*z)^nu);
if(a0==1,S0=S0+u);if(a1==1,S1=S1+u);if(a2==1,S2=S2+u);
L0=lift(S0);L1=lift(S1);L2=lift(S2);
j=Mod(y,y^2+y+1);Y=L0+j*L1+j^2*L2;nj=valuation(norm(Y),p);
print(f," ",P," vptor=",vptor," T_K=",L," A=",L0," ",L1," ",L2," ",nj))}}}
```

Let's give a partial table for  $p = 7$  and 13, in which  $vptor := v_p(\#\mathcal{T}_K)$  (examples limited to  $vptor \geq 2$ ), and  $nj = v_p(N_{\mathbb{Q}(j)/\mathbb{Q}}(\Lambda_0 + \Lambda_1 \cdot j + \Lambda_2 \cdot j^2))$ ; one sees that, as expected, all the examples give  $nj = vptor$  since  $\mathcal{T}_K$  is a finite  $\mathbb{Z}_7[j]$ -module which may be decomposed with two 7-adic characters:.

f	P	vptor	T_K	coefficients	nj
313	$x^3+x^2-104*x+371$	vptor=2	T_K=[7,7]	A=[41, 41, 48]	2
577	$x^3+x^2-192*x+171$	vptor=2	T_K=[49]	A=[183, 17, 280]	2
823	$x^3+x^2-274*x+61$	vptor=3	T_K=[343]	A=[761, 419, 437]	3
883	$x^3+x^2-294*x+1439$	vptor=2	T_K=[7,7]	A=[14, 0, 35]	2
1051	$x^3+x^2-350*x-2608$	vptor=2	T_K=[49]	A=[4, 247, 309]	2
1117	$x^3+x^2-372*x+2565$	vptor=2	T_K=[7,7]	A=[7, 7, 42]	2
1213	$x^3+x^2-404*x+629$	vptor=2	T_K=[49]	A=[45, 313, 268]	2
1231	$x^3+x^2-410*x-1003$	vptor=2	T_K=[49]	A=[247, 73, 273]	2

1237	$x^3+x^2-412*x+1741$	vptor=2	T_K=[49]	A=[108, 336, 128]	2
1297	$x^3+x^2-432*x-1345$	vptor=2	T_K=[49]	A=[277, 62, 14]	2
1327	$x^3+x^2-442*x-344$	vptor=2	T_K=[49]	A=[217, 340, 251]	2
1381	$x^3+x^2-460*x-1739$	vptor=4	T_K=[343,7]	A=[1738, 2186, 2361]	4
1567	$x^3+x^2-522*x-4759$	vptor=2	T_K=[49]	A=[219, 137, 78]	2
(...)					
2203	$x^3+x^2-734*x+408$	vptor=2	T_K=[7,7]	A=[28, 28, 35]	2
2251	$x^3+x^2-750*x-1584$	vptor=2	T_K=[49]	A=[191, 274, 151]	2
2557	$x^3+x^2-852*x+9281$	vptor=3	T_K=[49,7]	A=[235, 3, 286]	3

For  $f = 33199$ ,  $P = x^3 + x^2 - 11066x + 238541$ ,  $\mathcal{T}_K \simeq \mathbb{Z}/7\mathbb{Z} \times \mathbb{Z}/7\mathbb{Z}$ ,  $h = 14$ , and the annihilator is equivalent modulo  $1 + \sigma + \sigma^2$  to  $A = \sigma - 2$ .

For  $f = 20857$ ,  $P = x^3 + x^2 - 6952x + 210115$ ,  $\mathcal{T}_K \simeq \mathbb{Z}/7^2\mathbb{Z} \times \mathbb{Z}/7^2\mathbb{Z}$ ,  $h = 1$ , and the annihilator is equivalent to  $A = 7^2(\sigma - 3)$ .

For  $f = 1381$ ,  $\mathcal{T}_K \simeq \mathbb{Z}/7^3\mathbb{Z} \times \mathbb{Z}/7\mathbb{Z}$ ,  $h = 1$ ,  $A = 1738 + 2186\sigma + 2361\sigma^2$  is equivalent to  $7 \cdot (448 + 623\sigma)$  and  $448 + 623\sigma$  operates on  $\mathcal{T}_K^7 \simeq \mathbb{Z}/7^2\mathbb{Z}$  as  $\sigma - 18$  modulo  $7^2$  where 18 is of order 3 modulo  $7^2$  as expected.

For  $f = 39679$ ,  $\mathcal{T}_K \simeq \mathbb{Z}/7^3\mathbb{Z} \times \mathbb{Z}/7\mathbb{Z} \times \mathbb{Z}/7\mathbb{Z}$ ,  $h = 7$ , and one finds the annihilator  $A = 7^2(\sigma - 4)$ .

For  $p = 13$ , the same program gives the following similar results:

f	P	vptor	T_K	coefficients	nj
1033	$x^3+x^2-344*x+1913$	vptor=2	T_K=[169]	A=[311, 455, 919]	2
1459	$x^3+x^2-486*x+2864$	vptor=2	T_K=[13,13]	A=[101, 88, 153]	2
1483	$x^3+x^2-494*x-2197$	vptor=2	T_K=[169]	A=[911, 1868, 1628]	2
1543	$x^3+x^2-514*x+4229$	vptor=2	T_K=[169]	A=[1598, 603, 1866]	2
1747	$x^3+x^2-582*x-4141$	vptor=2	T_K=[169]	A=[1952, 505, 155]	2
3391	$x^3+x^2-1130*x+14192$	vptor=3	T_K=[169,13]	A=[803, 1765, 283]	3
4423	$x^3+x^2-1474*x+10648$	vptor=2	T_K=[169]	A=[52, 1213, 1888]	2
4933	$x^3+x^2-1644*x-1827$	vptor=2	T_K=[13,13]	A=[92, 79, 105]	2
5011	$x^3+x^2-1670*x-4083$	vptor=2	T_K=[169]	A=[602, 1673, 869]	2
5479	$x^3+x^2-1826*x+13799$	vptor=2	T_K=[13,13]	A=[93, 158, 28]	2
7321	$x^3+x^2-2440*x-45824$	vptor=2	T_K=[169]	A=[745, 409, 1546]	2
7963	$x^3+x^2-2654*x+43944$	vptor=2	T_K=[169]	A=[1805, 794, 860]	2
9319	$x^3+x^2-3106*x-67649$	vptor=2	T_K=[13,13]	A=[26, 52, 0]	2

## 6. EXPERIMENTS AND HEURISTICS ABOUT THE CASE $p = 2$

The Conjecture 5.7 gives various possibilities of annihilation, depending on the choice of  $\mathcal{A}_{K,n}(c)$ ,  $\mathcal{A}'_{K,n}(c)$  or else, and of the degree of  $K/\mathbb{Q}$ , odd, even, or a 2th power. We shall give some illustrations with quadratic, quartic and cubic fields.

**6.1. Quadratic fields,  $p = 2$ .** Although the order of  $\mathcal{T}_K$  is known and given by  $\frac{1}{2}L_2(1, \chi)$ , we give the computations for the quadratic fields  $K$  of conductor  $f \geq 5$  with  $\mathcal{A}'_{K,n}(c)$  ( $a \in [1, f_n/2]$ ) instead of  $\mathcal{A}_{K,n}(c)$  to test the conjecture; the computation of the Artin symbols is easily given by PARI with  $\text{kronecker}(f, a) = \pm 1$ . The modulus  $f_n = \text{l.c.m.}(f_K, 4 \cdot 2^n)$  is computed exactly and  $n = 2 + e$ .

From the annihilator  $A' = a_0 + a_1 \cdot \sigma$  (in  $(L_0, L_1)$ ), we deduce, modulo the norm, an equivalent annihilator  $a_1 - a_0 \in \mathbb{Z}$ .

One finds  $A \equiv 2 \cdot \#\mathcal{T}_K \pmod{2^{2+e}}$  for all  $f \neq 8$  (only case with  $K \cap \mathbb{Q}_\infty \neq \mathbb{Q}$ ) in this interval; then the class group is given (be careful to take  $nt$  large enough for the computation of the structure of  $\mathcal{T}_K$ ):

```

{p=2;nt=18;bf=5;Bf=10^4;for(f=bf,Bf,v=valuation(f,2);M=f/2^v;
if(core(M)!=M,next);if((v==1||v>3)|| (v==0 & Mod(M,4)!=1)||
(v==2 & Mod(M,4)==1),next);P=x^2-f;K=bnfinit(P,1);Kpn=bnrinit(K,p^nt);
C5=component(Kpn,5);Hpn0=component(C5,1);Hpn=component(C5,2);
h=component(component(component(K,8),1),2);L=listcreate;ex=0;
i=component(matsize(Hpn),2);R=0;for(k=1,i-1,co=component(Hpn,i-k+1);
if(Mod(co,p)==0,R=R+1;val=valuation(co,p);if(val>ex,ex=val);
listinsert(L,p^val,1));Hpn1=component(Hpn,1);
vptor=valuation(Hpn0/Hpn1,p);tor=p^vptor;S0=0;S1=0;w=valuation(f,p);
pN=p^2*p^ex;fn=pN*f/2^w;if(ex==0 & w==3,fn=p*fn);
for(cc=2,10^2,if(gcd(cc,p*f)!=1 || kronecker(f,cc)!=-1,next);c=cc;break);
for(a=1,fn/2,if(gcd(a,fn)!=1,next);asurc=lift(a*Mod(c,fn)^-1);
lambda=(asurc*c-a)/fn;u=Mod(lambda*a^-1,pN);
s=kronecker(f,a);if(s==1,S0=S0+u);if(s==-1,S1=S1+u));
L0=lift(S0);L1=lift(S1);A=L1-L0;if(A!=0,A=p^valuation(A,p));
print(f," P=",P," ",LO," ",L1," A=",A," tor=",tor," T_K=",L," Cl_K=",h)}}

f_K=8      P=x^2-8      (1, 0)      A'=1      tor=1      T_K=[]      Cl_K=[]
(...)
f_K=508    P=x^2-508    (223, 479)  A'=256   tor=128   T_K=[128]   Cl_K=[]
(...)
f_K=1160   P=x^2-1160   (2, 6)     A'=4     tor=2     T_K=[2]     Cl_K=[2,2]
f_K=1164   P=x^2-1164   (12, 4)    A'=8     tor=4     T_K=[4]     Cl_K=[4]
(...)
f_K=1185   P=x^2-1185   (1640, 1640) A'=0     tor=1024  T_K=[2,512] Cl_K=[2]
f_K=1189   P=x^2-1189   (2, 6)     A'=4     tor=2     T_K=[2]     Cl_K=[2]
(...)
f_K=1196   P=x^2-1196   (4, 20)    A'=16    tor=8     T_K=[8]     Cl_K=[2]
f_K=1201   P=x^2-1201   (7752, 3656) A'=4096  tor=2048  T_K=[2048]  Cl_K=[]
(...)
f_K=1209   P=x^2-1209   (4, 4)     A'=0     tor=4     T_K=[2,2]   Cl_K=[2]
(...)
f_K=1217   P=x^2-1217   (16, 48)   A'=32    tor=16    T_K=[16]    Cl_K=[]
f_K=1221   P=x^2-1221   (8, 8)     A'=0     tor=8     T_K=[2,4]   Cl_K=[4]
(...)
f_K=1596   P=x^2-1596   (16, 16)   A'=0     tor=16    T_K=[8, 2]  Cl_K=[4,2]

```

*Remarks 6.1.* (i) For  $f = 1160$ , one sees that  $\#\mathcal{C}_K^\infty = \frac{1}{2}\#\mathcal{C}_K$  (indeed,  $-1$  is norm in  $K/\mathbb{Q}$ , cf. (2.1)).

(ii) It seems that for all the conductors,  $A'$  is of the form  $2^h(1 + \sigma)$  up to a 2-adic unit, where  $h \geq 0$  takes any value and can exceed the exponent.

(iii) For  $f = 1201$ , the annihilator of  $\mathcal{T}_K$  given by the Theorem 9.4, or by any Solomon's type element, is related to its order:

$$\frac{1}{2}L_2(1, \chi) \sim \frac{1}{2} \sum_{a=1}^f \chi(a) \cdot \log(1 - \zeta_f^a) = \frac{1}{2} \cdot [\log(\eta_K) - \log(\eta_K^\sigma)],$$

where  $\eta_K = N_{\mathbb{Q}^f/K}(1 - \zeta_f)$  (here the character  $\chi$  is primitive modulo  $f$  since  $K = k_\chi$ ). The following program verifies (at least for these kind of prime conductors with trivial class group) that we have  $\eta_K \cdot \varepsilon = \pm\sqrt{f}$ , where  $\varepsilon$  is the fundamental unit of  $K$  or its inverse (the program gives in  $N_0$  and  $N_1$  the conjugates of  $\eta_K$  and gives  $\varepsilon$  in  $E$ ):

```

{f=1201;N0=1;N1=1;X=exp(2*I*Pi/f);z=znprimroot(f);E=quadunit(f);zk=1;
for(k=1,(f-1)/2,zk=zk*z^2;N0=N0*(1-X^lift(zk));N1=N1*(1-X^lift(zk*z)));
print(N0*E," ",N1/E)}

```

We find  $N_0 \varepsilon = N_1 \varepsilon^{-1} \approx 34.65544690 = \sqrt{1201}$ , which implies that:

$$\frac{1}{2} L_2(1, \chi) \sim \frac{1}{2} (2 \log(\varepsilon)) = \log(\varepsilon).$$

A direct computation gives  $\log(\varepsilon) \sim 2^{12}$  as expected since  $\#\mathcal{T}_K = 2^{11}$  with  $\#\mathcal{R}_K \sim 2^{10}$  [9, Proposition 5.2] and  $\#\mathcal{W}_K = 2$  since 2 splits in  $K$ . Same kind of result with  $f = 1217$ .

## 6.2. A family of cyclic quartic fields (composite conductors, $p = 2$ ).

We consider a conductor  $f$  product of two prime numbers  $q_1$  and  $q_2$  such that  $q_1 - 1 \equiv 2 \pmod{4}$  and  $q_2 - 1 \equiv 0 \pmod{8}$ . So there exists only one real cyclic quartic field  $K$  of conductor  $f$  which is found eliminating the imaginary and non-cyclic fields; the quadratic subfield of  $K$  is  $k = \mathbb{Q}(\sqrt{q_2})$ . The program is written with  $\mathcal{A}'_{K,n}(c)$  and gives all information for  $k$  and  $K$ . The following result may help to precise the annihilations for real cyclic quartic fields (see [8, Theorem IV.3.3, Exercise IV.3.3.1]):

**Lemma 6.2.** *Let  $k$  be a totally real number field and let  $K/k$  be a Galois  $p$ -extension with Galois group  $g$  of order  $p^r$ . Then  $\#\mathcal{T}_K^g = \#\mathcal{T}_k \cdot p^h$ , where  $h := \min(n_0 + r; \dots, \nu_l + \varphi_l + \gamma_l, \dots) - (n_0 + r) + \sum_{\mathfrak{l} \mid p} e_l$ , with:*

$$\begin{aligned} p^{\nu_l} &:= p\text{-part of } q^{-1} \log(\ell), \text{ where } \mathfrak{l} \cap \mathbb{Z} =: \ell \mathbb{Z}, \\ p^{\varphi_l} &:= p\text{-part of the residue degree of } \ell \text{ in } K/\mathbb{Q}, \\ p^{\gamma_l} &:= p\text{-part of the number of prime ideal } \mathfrak{L} \mid \mathfrak{l} \text{ in } K/k, \\ p^{e_l} &:= p\text{-part of the ramification index of } \mathfrak{l} \text{ in } K/k. \end{aligned}$$

In the present family,  $h = 2$  (resp. 3) if  $q$  is inert (resp. splits) in  $k/\mathbb{Q}$ .

```
{p=2;nt=18;forprime(qq=17,100,if(Mod(qq,8)!=1,next));Pk=x^2-qq;
k=bnfinit(Pk,1);kpn=bnrinit(k,p^nt);Hkpn=component(component(kpn,5),2);
Lk=listcreate;i=component(matsize(Hkpn),2);R=0;
for(j=1,i-1,C=component(Hkpn,i-j+1);if(Mod(C,p)==0,R=R+1;
listinsert(Lk,p^valuation(C,p),1));forprime(q=5,100,
if(valuation(q-1,2)!=2,next);f=q*qq;Q=polsubcyclo(f,4);
for(j=1,7,P=component(Q,j);K=bnfinit(P,1);C7=component(K,7);
S=component(C7,2);D=component(C7,3);
if(Mod(D,f)!=0 || S!=[4,0] || component(polgalois(P),2)!=-1,next);break);
h=component(component(component(K,8),1),2);Kpn=bnrinit(K,p^nt);
C5=component(Kpn,5);Hpn0=component(C5,1);Hpn=component(C5,2);
Hpn=component(component(Kpn,5),2);L=listcreate;ex=0;
i=component(matsize(Hpn),2);R=0;for(k=1,i-1,co=component(Hpn,i-k+1);
if(Mod(co,p)==0,R=R+1;val=valuation(co,p);if(val>ex,ex=val);
listinsert(L,p^val,1));Hpn1=component(Hpn,1);
vptor=valuation(Hpn0/Hpn1,p);if(vptor>0,S0=0;S1=0;S2=0;S3=0;
pN=p^2*p^ex;fn=pN*f;dqq=(qq-1)/4;dq=(q-1)/2;
z=znprimroot(q);zz=znprimroot(qq);for(cc=3,f,if(gcd(cc,p*f)!=1,next);
cz=lift((cc*z)^dq);czz=lift((cc*zz)^dqq);if(cz!=1 || czz!=1,next);
c=cc;break);cm1=Mod(c,fn)^-1;for(a=1,fn/2,if(gcd(a,fn)!=1,next);
asurc=lift(a*cm1);lambda=(asurc*c-a)/fn;u=Mod(lambda*a^-1,pN);
aqq0=lift((a*zz^0)^dq);aqq1=lift((a*zz^1)^dq);
aqq2=lift((a*zz^2)^dq);aqq3=lift((a*zz^3)^dq);
aq0=lift((a*z^0)^dq);aq1=lift((a*z^1)^dq);
if(aqq0==1 & aq0==1,S0=S0+u);if(aqq1==1 & aq1==1,S2=S2+u);
if(aqq2==1 & aq2==1,S1=S1+u);if(aqq3==1 & aq3==1,S3=S3+u);
if(aqq0==1 & aq0==1,S2=S2+u);if(aqq1==1 & aq1==1,S0=S0+u);
if(aqq2==1 & aq2==1,S3=S3+u);if(aqq3==1 & aq3==1,S1=S1+u);
L0=lift(S0);L1=lift(S1);L2=lift(S2);L3=lift(S3);Y=Mod(y,y^2+1);
```

```

ni=L0+Y*L1+Y^2*L2+Y^3*L3;Nni=valuation(norm(ni),2);V0=1;V1=1;V2=1;V3=1;
if(L0!=0,V0=2^valuation(L0,2));if(L1!=0,V1=2^valuation(L1,2));
if(L2!=0,V2=2^valuation(L2,2));if(L3!=0,V3=2^valuation(L3,2));
print();F=component(factor(f),1);
print("f=",F," h=",h," P=",P," tor=",2^vptor," Nni=",2^Nni);
print("A=",V0,"*",L0/V0," ",V1,"*",L1/V1," ",V2,"*",L2/V2," ",V3,"*",L3/V3);
print("q=",q," qq=",qq," T_k=",Lk," T_K=",L))}

```

```

f=[5, 17] h=[2] P=x^4-x^3-23*x^2+x+86 tor=16 Nni=16
A=[2*5, 4*1, 2*1, 1*0] q=5 qq=17 T_k=List([2]) T_K=[4, 2, 2]
f=[13, 17] h=[2] P=x^4-x^3-57*x^2+x+664 tor=32 Nni=32
A=[2*1, 2*1, 2*3, 2*3] q=13 qq=17 T_k=[2] T_K=[4, 4, 2]
f=[17, 29] h=[2] P=x^4-x^3-125*x^2+x+3452 tor=16 Nni=16
A=[4*3, 2*1, 1*0, 2*1] q=29 qq=17 T_k=[2] T_K=[4, 2, 2]
f=[17, 37] h=[10] P=x^4-x^3-159*x^2+x+5662 tor=16 Nni=16
A=[4*1, 2*3, 8*1, 2*7] q=37 qq=17 T_k=[2] T_K=[4, 2, 2]
f=[17, 53] h=[2, 2] P=x^4-x^3-227*x^2+x+11714 tor=32 Nni=32
A=[2*1, 2*5, 2*3, 2*7] q=53 qq=17 T_k=[2] T_K=[4, 4, 2]
f=[17, 61] h=[2] P=x^4-x^3-261*x^2+x+15556 tor=16 Nni=16
A=[2*1, 8*1, 2*5, 4*3] q=61 qq=17 T_k=[2] T_K=[4, 2, 2]
f=[5, 41] h=[2] P=x^4-x^3-56*x^2-100*x+160 tor=256 Nni=32
A=[2*13, 2*45, 2*59, 2*27] q=5 qq=41 T_k=[16] T_K=[32, 4, 2]
f=[13, 41] h=[2] P=x^4-x^3-138*x^2-264*x+1472 tor=256 Nni=32
A=[2*13, 2*27, 2*51, 2*5] q=13 qq=41 T_k=[16] T_K=[32, 4, 2]
f=[29, 41] h=[2] P=x^4-x^3-302*x^2-592*x+8032 tor=1024 Nni=128
A=[4*21, 4*5, 4*15, 4*15] q=29 qq=41 T_k=[16] T_K=[32, 8, 4]
f=[37, 41] h=[2] P=x^4-x^3-384*x^2-756*x+13280 tor=256 Nni=32
A=[2*57, 2*7, 2*47, 2*33] q=37 qq=41 T_k=[16] T_K=[32, 4, 2]
f=[41, 53] h=[2] P=x^4-x^3-548*x^2-1084*x+27712 tor=512 Nni=64
A=[4*23, 8*15, 4*5, 8*7] q=53 qq=41 T_k=[16] T_K=[32, 4, 4]
f=[41, 61] h=[2, 2] P=x^4-x^3-630*x^2-1248*x+36896 tor=8192 Nni=1024
A=[32*3, 16*7, 1*0, 16*7] q=61 qq=41 T_k=[16] T_K=[32, 16, 16]
f=[5, 73] h=[2] P=x^4-x^3-100*x^2+187*x+1389 tor=8 Nni=8
A=[1*5, 1*9, 1*15, 1*3] q=5 qq=73 T_k=[2] T_K=[4, 2]
f=[13, 73] h=[2] P=x^4-x^3-246*x^2+479*x+11171 tor=8 Nni=8
A=[1*7, 1*13, 1*13, 1*15] q=13 qq=73 T_k=[2] T_K=[4, 2]
f=[29, 73] h=[2] P=x^4-x^3-538*x^2+1063*x+58767 tor=8 Nni=8
A=[1*5, 1*7, 1*15, 1*5] q=29 qq=73 T_k=[2] T_K=[4, 2]
f=[37, 73] h=[2] P=x^4-x^3-684*x^2+1355*x+96581 tor=128 Nni=128
A=[1*0, 16*1, 8*1, 8*1] q=37 qq=73 T_k=[2] T_K=[8, 8, 2]
f=[53, 73] h=[10] P=x^4-x^3-976*x^2+1939*x+200241 tor=8 Nni=8
A=[1*15, 1*15, 1*5, 1*13] q=53 qq=73 T_k=[2] T_K=[4, 2]
f=[61, 73] h=[2] P=x^4-x^3-1122*x^2+2231*x+266087 tor=16 Nni=16
A=[8*1, 2*3, 1*0, 2*1] q=61 qq=73 T_k=[2] T_K=[4, 2, 2]
f=[5, 89] h=[2, 2] P=x^4-x^3-122*x^2-217*x+1699 tor=16 Nni=16
A=[1*0, 2*1, 8*1, 2*3] q=5 qq=89 T_k=[2] T_K=[4, 2, 2]
f=[13, 89] h=[2] P=x^4-x^3-300*x^2-573*x+13625 tor=8 Nni=8
A=[1*1, 1*7, 1*11, 1*13] q=13 qq=89 T_k=[2] T_K=[4, 2]
f=[29, 89] h=[2] P=x^4-x^3-656*x^2-1285*x+71653 tor=8 Nni=8
A=[1*11, 1*5, 1*1, 1*15] q=29 qq=89 T_k=[2] T_K=[4, 2]
f=[37, 89] h=[2] P=x^4-x^3-834*x^2-1641*x+117755 tor=8 Nni=8
A=[1*9, 1*15, 1*3, 1*5] q=37 qq=89 T_k=[2] T_K=[4, 2]
f=[53, 89] h=[2] P=x^4-x^3-1190*x^2-2353*x+244135 tor=16 Nni=16
A=[4*1, 2*5, 4*1, 2*7] q=53 qq=89 T_k=[2] T_K=[4, 2, 2]
f=[61, 89] h=[2] P=x^4-x^3-1368*x^2-2709*x+324413 tor=8 Nni=8
A=[1*1, 1*9, 1*11, 1*11] q=61 qq=89 T_k=[2] T_K=[4, 2]
f=[5, 97] h=[2] P=x^4-x^3-133*x^2-479*x+36 tor=16 Nni=16
A=[2*5, 8*1, 2*1, 4*3] q=5 qq=97 T_k=[2] T_K=[4, 2, 2]

```



```

f=[13, 97]   h=[10] P=x^4-x^3-327*x^2-1255*x+2558 tor=16 Nni=16
  A=[4*1, 2*7, 8*1, 2*3]   q=13 qq=97 T_k=[2] T_K=[4, 2, 2]
f=[29, 97]   h=[2] P=x^4-x^3-715*x^2-2807*x+16914 tor=16 Nni=16
  A=[2*3, 8*1, 2*3, 4*3]   q=29 qq=97 T_k=[2] T_K=[4, 2, 2]
f=[37, 97]   h=[2] P=x^4-x^3-909*x^2-3583*x+28748 tor=16 Nni=16
  A=[4*3, 2*7, 1*0, 2*3]   q=37 qq=97 T_k=[2] T_K=[4, 2, 2]
f=[53, 97]   h=[2] P=x^4-x^3-1297*x^2-5135*x+61728 tor=64 Nni=64
  A=[8*3, 4*7, 16*1, 4*7] q=53 qq=97 T_k=[2] T_K=[8, 4, 2]
f=[61, 97]   h=[2] P=x^4-x^3-1491*x^2-5911*x+82874 tor=32 Nni=32
  A=[2*7, 2*5, 2*5, 2*7] q=61 qq=97 T_k=[2] T_K=[4, 4, 2]

```

One may try to find a contradiction to Conjecture 5.7 with the  $\mathcal{A}'_{K,n}(c)$  given by the above data. One sees that  $\frac{1}{2}\mathcal{A}'_{K,n}(c)$  is not always in  $\mathbb{Z}[G_K]$ , but modulo the norm we have an annihilator of the form  $2 \cdot \mathcal{A}''_{K,n}(c)$ , and similarly we may ask under what condition  $\mathcal{A}''_{K,n}(c)$  annihilates  $\mathcal{T}_K$ .

For instance, for  $f = 5 \cdot 73$ ,  $P = x^4 - x^3 - 100x^2 + 187x + 1389$ , for which  $\mathcal{T}_K \simeq \mathbb{Z}/4\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ ,  $\mathcal{T}_k \simeq \mathbb{Z}/2\mathbb{Z}$ ,  $h = 2$ ,  $\mathcal{A}'_{K,n}(c) = 5 + 9\sigma + 15\sigma^2 + 3\sigma^3$ , giving  $\mathcal{A}''_{K,n}(c) = \frac{1}{2}[5 + 9\sigma + 15\sigma^2 + 3\sigma^3 - 3(1 + \sigma + \sigma^2 + \sigma^3)] \equiv 1 - \sigma + 2\sigma^2 \pmod{4}$  without obvious contradiction since  $\#\mathcal{T}_K^g = 8$  and  $\#\mathcal{T}_K^{G_K} = 4$  (Lemma 6.2).

**6.3. Cyclic cubic fields of prime conductors,  $p = 2$ .** The following program gives, for  $p = 2$  and for cyclic cubic fields of prime conductor  $f$ , the group structure of  $\mathcal{T}_K$  in  $L$  (from [10, §3.2]; note that in all such programs, the parameter  $nt$  must be large enough regarding the exponent of  $\mathcal{T}_K$ ), then the (conjectural) annihilator  $\mathcal{A}'_{K,n}(c)$ , reduced modulo  $1 + \sigma + \sigma^2$ ; it is equal, up to an invertible element, to a power of 2 (2 is inert in  $\mathbb{Q}(j)$ ):

```

{p=2;nt=12;forprime(f=10^4,2*10^4,if(Mod(f,3)!=1,next);P=polsubcyclo(f,3);
K=bnfinit(P,1);Kpn=bnrinit(K,p^nt);C5=component(Kpn,5);
Hpn0=component(C5,1);Hpn=component(C5,2);L=listcreate;ex=0;
i=component(matsize(Hpn),2);R=0;for(k=1,i-1,co=component(Hpn,i-k+1);
if(Mod(co,p)==0,R=R+1;val=valuation(co,p);if(val>ex,ex=val);
listinsert(L,p^val,1));Hpn1=component(Hpn,1);
vptor=valuation(Hpn0/Hpn1,p);if(vptor>2,S0=0;S1=0;S2=0;pN=p^2*p^ex;
D=(f-1)/3;fn=pN*f;z=znprimroot(f);zz=lift(z);t=lift(Mod((1-zz)/f,p));
c=zz+t*f;for(a=1,fn/2,if(gcd(a,fn)!=1,next);asurc=lift(a*Mod(c,fn)^-1);
lambda=(asurc*c-a)/fn;u=Mod(lambda*a^-1,pN);
a0=lift((a*z^0)^D);a1=lift((a*z^2)^D);a2=lift((a*z)^D);
if(a0==1,S0=S0+u);if(a1==1,S1=S1+u);if(a2==1,S2=S2+u);
L0=lift(S0);L1=lift(S1);L2=lift(S2);L1=L1-L0;L2=L2-L0;
A=gcd(L1,L2);A=2^valuation(A,2);print(f," ",P," ",A," ",L))}

```

f	P	A	L
10399	$x^3+x^2-3466*x+7703$	4	[4,4]
10513	$x^3+x^2-3504*x-80989$	8	[8,8]
10753	$x^3+x^2-3584*x-76864$	4	[4,4]
10771	$x^3+x^2-3590*x-26728$	4	[4,4]
10903	$x^3+x^2-3634*x+26248$	8	[8,8]
10939	$x^3+x^2-3646*x-46592$	16	[16,16]
10957	$x^3+x^2-3652*x-39364$	4	[4,4]
11149	$x^3+x^2-3716*x+39228$	4	[2,2,2,2]
(...)			
12757	$x^3+x^2-4252*x+103001$	4	[4,4]
13267	$x^3+x^2-4422*x+96800$	16	[16,16]
13297	$x^3+x^2-4432*x+94064$	4	[4,4]
13309	$x^3+x^2-4436*x+100064$	4	[4,4]
13591	$x^3+x^2-4530*x-63928$	8	[8,8]

**6.4. Cyclic quartic fields of prime conductors,  $p = 2$ .** Let's give the same program for prime conductors  $f \equiv 1 \pmod{8}$ , with the annihilator  $\mathcal{A}_{K,n}(c)$ :

```
{p=2;nt=18;d=4;forprime(f=5,500,if(Mod(f,2*d)!=1,next);P=polsubcyclo(f,d);
K=bnfinit(P,1);Kpn=bnrinit(K,p^nt);C5=component(Kpn,5);Hpn0=component(C5,1);
Hpn=component(C5,2);L=listcreate;ex=0;
i=component(matsize(Hpn),2);R=0;for(k=1,i-1,co=component(Hpn,i-k+1);
if(Mod(co,p)==0,R=R+1;val=valuation(co,p);if(val>ex,ex=val);
listinsert(L,p^val,1));Hpn1=component(Hpn,1);
vptor=valuation(Hpn0/Hpn1,p);if(vptor>1,S0=0;S1=0;S2=0;S3=0;
pN=p^2*p^ex;D=(f-1)/d;fn=pN*f;z=znprimroot(f);zz=lift(z);
t=lift(Mod((1-zz)/f,p));c=zz+t*f;for(a=1,fn,if(gcd(a,fn)!=1,next);
asurc=lift(a*Mod(c,fn)^-1);lambda=(asurc*c-a)/fn;u=Mod(lambda*a^-1,pN);
a0=lift((a*z^0)^D);a1=lift((a*z^1)^D);a2=lift((a*z^2)^D);a3=lift((a*z^3)^D);
if(a0==1,S0=S0+u);if(a1==1,S1=S1+u);if(a2==1,S2=S2+u);if(a3==1,S3=S3+u);
L0=lift(S0);L1=lift(S1);L2=lift(S2);L3=lift(S3);Y=Mod(y,y^2+1);
ni=L0+Y*L1+Y^2*L2+Y^3*L3;Nni=valuation(norm(ni),2);
print(f," ",P," ",L0," ",L1," ",L2," ",L3," ",L," ",2^Nni))}
```

One gets the following examples (with  $vptor > 1$  and where  $2^{Nni}$  is the norm of  $L_0 - L_2 + (L_1 - L_3)\sqrt{-1}$  where  $\mathcal{A}_{K,n}(c) = L_0 + L_1\sigma + L_2\sigma^2 + L_3\sigma^3$ ):

f	P	A	L	$2^{Nni}$
17	$x^4+x^3-6x^2-x+1$	[4, 6, 0, 6]	[4]	16
41	$x^4+x^3-15x^2+18x-4$	[90, 28, 102, 100]	[32]	16
73	$x^4+x^3-27x^2-41x+2$	[4, 4, 0, 0]	[2,2,2]	32
89	$x^4+x^3-33x^2+39x+8$	[4, 4, 0, 0]	[2,2,2]	32
97	$x^4+x^3-36x^2+91x-61$	[8, 10, 12, 2]	[4]	16
113	$x^4+x^3-42x^2-120x-64$	[16, 28, 8, 12]	[2,2,8]	64
137	$x^4+x^3-51x^2-214x-236$	[26, 8, 30, 16]	[16]	16
193	$x^4+x^3-72x^2-205x-49$	[6, 0, 14, 12]	[4]	16
233	$x^4+x^3-87x^2+335x-314$	[4, 0, 0, 4]	[2,2,2]	32
241	$x^4+x^3-90x^2-497x-739$	[6, 0, 6, 4]	[4]	16
257	$x^4+x^3-96x^2-16x+256$	[28, 20, 20, 60]	[2,4,16]	128
281	$x^4+x^3-105x^2+123x+236$	[4, 4, 0, 0]	[2,2,2]	32
313	$x^4+x^3-117x^2+450x-324$	[78, 12, 106, 108]	[32]	16
337	$x^4+x^3-126x^2+316x+104$	[28, 12, 28, 28]	[2,8,8]	256
353	$x^4+x^3-132x^2+684x-928$	[112, 60, 80, 68]	[2,2,32]	64
401	$x^4+x^3-150x^2-25x+625$	[14, 4, 6, 8]	[4]	16
409	$x^4+x^3-153x^2-230x+548$	[22, 8, 26, 24]	[8]	16
433	$x^4+x^3-162x^2+839x-1003$	[2, 4, 10, 0]	[4]	16
449	$x^4+x^3-168x^2-477x+335$	[10, 4, 10, 8]	[4]	16
457	$x^4+x^3-171x^2+1114x-2044$	[76, 10, 28, 30]	[32]	16

**6.5. Detailed example of annihilation for  $p = 2$ .** The case of the cyclic quartic field  $K$  of conductor  $f = 3433$  is particularly interesting:

**6.5.1. Numerical data.** We have  $P = x^4 + x^3 - 1287x^2 - 12230x + 3956$  and  $\mathcal{T}_K \simeq \mathbb{Z}/2^7\mathbb{Z}$ , knowing that the quadratic subfield  $k$  is such that  $\mathcal{T}_k \simeq \mathbb{Z}/2^6\mathbb{Z}$ :

```
{P=x^4+x^3-1287*x^2-12230*x+3956;K=bnfinit(P,1);p=2;nt=18;
Kpn=bnrinit(K,p^nt);Hpn=component(component(Kpn,5),2);
L=listcreate;i=component(matsize(Hpn),2);
for(k=1,i-1,c=component(Hpn,i-k+1);if(Mod(c,p)==0,
listinsert(L,p^valuation(c,p),1));print("Structure: ",L)}
Structure: List([128])
{P=x^2-3433;K=bnfinit(P,1);p=2;nt=18;Kpn=bnrinit(K,p^nt);
Hpn=component(component(Kpn,5),2);L=listcreate;
i=component(matsize(Hpn),2);
```

```
for(k=1,i-1,c=component(Hpn,i-k+1);if(Mod(c,p)==0,
listinsert(L,p^valuation(c,p),1));print("Structure: ",L)}
Structure: List([64])
```

The class group of  $K$  is trivial and its units are:

```
[227193/338*x^3-6613325/338*x^2-93274465/338*x+14925255/169,
34349/169*x^3+1388772/169*x^2+10559389/169*x-3491425/169,
70276336974818125/338*x^3-677429229869394661/338*x^2
-83238272983560888143/338*x+13065197272033438434/169]
```

6.5.2. *Annihilation from  $\mathcal{A}_{K,n}(c)$ .* We have computed  $\mathcal{A}_{K,n}(c)$  and obtained:

$$\mathcal{A}_{K,n}(c) =: A_K \equiv 8 \cdot 13 + 2 \cdot 21 \sigma + 16 \cdot 7 \sigma^2 + 2 \cdot 23 \sigma^3 \pmod{2^7}.$$

Let  $h$  be a group generator of  $\mathcal{T}_K$  (order  $2^7$ ) and let  $h_0$  be a generator of  $\mathcal{T}_k$  (order  $2^6$ ); it is easy to prove that one may suppose  $h^2 = j_{K/k}(h_0)$  (injectivity of the transfer map  $j_{K/k}$ ) and  $h_0^2 = h_0$ . We put  $j_{K/k}(h_0) =: h_0$  for simplicity. Then it follows that

$$h^{A_K} = h_0^{4 \cdot 13 + 21 \sigma + 8 \cdot 7 \sigma^2 + 23 \sigma^3} = 1.$$

Since  $h_0^2 = h_0$ , we obtain  $h^{A_K} = h_0^{(4 \cdot 13 + 8 \cdot 7) + (21 + 23) \bar{\sigma}} = h_0^{4 \cdot 27 + 4 \cdot 11 \bar{\sigma}} = 1$ ; giving, modulo the norm  $1 + \bar{\sigma}$ ,  $h_0^{4 \cdot (27 - 11)} = h_0^{26} = 1$ , as expected.

6.5.3. *Annihilation from  $\mathcal{A}'_{K,n}(c)$ .* There is (by accident ?) no numerical obstruction for an annihilation by  $A'_K := \mathcal{A}'_{K,n}(c)$ , with the same program replacing “*for(a = 1, fn, ...)*” by “*for(a = 1, fn/2, ...)*”. Then it follows that the program gives  $h^{A'_K} = h^{4 \cdot 13 + 21 \sigma + 8 \cdot 15 \sigma^2 + 23 \sigma^3} = 1$ . Since the restriction of  $A'_K$  to  $k$  is  $A'_k$  (no Euler factors), we get:

$$h_0^{A'_k} = h_0^{4 \cdot 13 + 8 \cdot 15 + (21 + 23) \cdot \bar{\sigma}} = h_0^{4 \cdot 43 + 4 \cdot 11 \bar{\sigma}} = 1$$

which is equivalent, modulo the norm, to the annihilation by  $4 \cdot 43 - 4 \cdot 11 = 2^7$  for a cyclic group of order  $2^6$ .

Now we may return to the annihilation of  $h$ ; since  $h^{1+\sigma^2} \in j_{K/k}(\mathcal{T}_k)$  we put  $h^{1+\sigma^2} = h_0^t$ . Then, with  $u = 13$ ,  $v = 21$ ,  $w = 15$ ,  $z = 23$ , we have:

$$\begin{aligned} h^{4u+v\sigma+8w\sigma^2+z\sigma^3} &= h_0^{2u+4w\sigma^2} h^{(v+z\sigma^2)\sigma} \\ &= h_0^{2u+4w+23t\sigma} h^{(v-z)\sigma} = h_0^{2 \cdot 43 + 23t\sigma} h^{-2\sigma} \\ &= h_0^{2 \cdot 43 + (23t-1)\sigma} = h_0^{2 \cdot 43 - 23t + 1} = h_0^{87 - 23t} = 1 \end{aligned}$$

so necessarily  $87 - 23t \equiv 0 \pmod{2^6}$ , giving  $t \equiv 1 \pmod{2^6}$ . So we can write:

$$h^{1+\sigma^2} = j_{K/k}(h_0).$$

6.5.4. *Direct study of the  $G_K$ -module structure of  $\mathcal{T}_K$ .* We consider  $\mathcal{T}_K$  only given with the following information:  $h$  is a group generator such that  $h^2 = h_0$ , a generator of  $j_{K/k}(\mathcal{T}_K)$ ;  $h^\sigma = h^x$ ,  $x \in \mathbb{Z}/2^7\mathbb{Z}$ , whence  $h_0^\sigma = h_0^x = h_0^{-1}$  giving  $x \equiv -1 \pmod{2^6}$ . The relation  $h^{\sigma^2+1} = h^{x^2+1} = h^2 = h_0$  gives again  $t = 1$  in the previous notation  $h^{\sigma^2+1} = h_0^t$ . Moreover,  $h^{\sigma^2-1} = h^{x^2-1} = 1$ , which is in accordance with Lemma 6.2 and gives  $\mathcal{T}_K^g = \mathcal{T}_K$ .

If we take into account these theoretical informations for the “annihilators”  $A_K$  and  $A'_K$  we find no contradiction, but we do not know if  $x = -1$  or

$x = -1 + 2^6$  (modulo  $2^7$ ). The prime 2 splits in  $k$ , is inert in  $K/k$  and the class number of  $K$  is 1; so we have  $\mathcal{W}_K \simeq \mathcal{W}_k \simeq \mathbb{Z}/2\mathbb{Z}$  and  $\mathcal{T}_K = \text{tor}_{\mathbb{Z}_2}(U_K/\overline{E}_K)$ ; then the result about  $x$  depends on the exact sequence (2.2):

$$1 \rightarrow \mathbb{Z}/2\mathbb{Z} \rightarrow \mathcal{T}_K \simeq \mathbb{Z}/2^7\mathbb{Z} \xrightarrow{\log} \text{tor}_{\mathbb{Z}_2}(\log(U_K)/\log(\overline{E}_K)) =: \mathcal{R}_K \rightarrow 0,$$

knowing the units and then the structure of the regulator  $\mathcal{R}_K$ .

**6.6. About the case  $f_K = 233$ .** The field  $K$  is defined by the polynomial  $P = x^4 + x^3 - 87x^2 + 335x - 314$  for which  $\mathcal{T}_K \simeq (\mathbb{Z}/2\mathbb{Z})^3$  and  $\mathcal{T}_k \simeq \mathbb{Z}/2\mathbb{Z}$ . In this case an annihilator is  $A_K = 4 \cdot (1 + \sigma^3) \equiv 0 \pmod{2}$ , which shows that  $A'_K = 2 \cdot (1 + \sigma^3)$  is also suitable. Then  $A''_K = \frac{1}{2}A'_K$  should be equivalent to  $1 - \sigma$ .

Since 2 splits completely in  $K$ , we have  $\mathcal{T}_K = \mathcal{W}_K \simeq (\mathbb{Z}/2\mathbb{Z})^3$  and in the same way,  $\mathcal{T}_k = \mathcal{W}_k \simeq \mathbb{Z}/2\mathbb{Z}$ , for which the Galois structures are well-known: in particular,  $1 - \sigma$  *does not annihilate*  $\mathcal{T}_K$  (the class of  $(1, -1, 1, -1)$  is invariant). Another proof: see Lemma 6.2 giving here  $\#\mathcal{T}_K^{G_K} = 2$ .

## 7. $p$ -ADIC MEASURES AND ANNIHILATIONS

To establish (in Section 9) a link with the values of  $p$ -adic  $L$ -functions,  $L_p(s, \chi)$ , at  $s = 1$ , we shall refer to [13, Section II] using the point of view of explicit  $p$ -adic measures (from pseudo-measures in the sense of [23]) with a Mellin transform for the construction of  $L_p(s, \chi)$  and the application to some properties of the  $\lambda$  invariants of Iwasawa's theory.

But since we only need the value  $L_p(1, \chi)$ , instead of  $L_p(s, \chi)$ , we can simplify the general setting, using a similar computation of  $\mathcal{S}_{L_n}(c)^*$ , directly in  $\mathbb{Z}[G_n]$ , given by Oriat in [21, Proposition 3.5].

**7.1. Definition of  $\mathcal{A}_{L_n}$  and  $\mathcal{A}_{L_n}(c)$ .** Let  $n \geq n_0 + e$  where  $\mathcal{T}_K^{p^e} = 1$ , and put  $\varphi_n := \varphi(qp^n) = (p-1) \cdot p^n$  if  $p \neq 2$ , and  $\varphi_n = 2^{n+1}$  otherwise.

We consider (where  $c$  is odd and prime to  $f_n$  and where  $a$  runs through the integers in  $[1, f_n]$ , prime to  $f_n$ ):

$$(7.1) \quad \mathcal{A}_{L_n} := \frac{-1}{f_n \varphi_n} \sum_a a^{\varphi_n} \left( \frac{L_n}{a} \right) \quad \& \quad \mathcal{A}_{L_n}(c) := \left[ 1 - c^{\varphi_n} \left( \frac{L_n}{c} \right) \right] \mathcal{A}_{L_n}.$$

For now, these elements, or more precisely their restrictions to  $K$ , are not to be confused with the restriction  $\mathcal{A}_{K,n}(c)$  of  $\mathcal{S}_{L_n}(c)^*$  defined in § 5.2. Then:

$$\begin{aligned} \mathcal{A}_{L_n}(c) &= \left[ 1 - c^{\varphi_n} \left( \frac{L_n}{c} \right) \right] \frac{-1}{f_n \varphi_n} \sum_a a^{\varphi_n} \left( \frac{L_n}{a} \right) \\ &\cong \frac{-1}{f_n \varphi_n} \left[ \sum_a a^{\varphi_n} \left( \frac{L_n}{a} \right) - \sum_a a^{\varphi_n} c^{\varphi_n} \left( \frac{L_n}{a} \right) \left( \frac{L_n}{c} \right) \right] \\ &\quad (\text{in the same way, use } a'_c \text{ such that} \\ &\quad \quad a'_c \cdot c \equiv a \pmod{f_n}, 1 \leq a'_c \leq f_n) \\ &\cong \frac{-1}{f_n \varphi_n} \left[ \sum_a a^{\varphi_n} \left( \frac{L_n}{a} \right) - \sum_a a'_c{}^{\varphi_n} c^{\varphi_n} \left( \frac{L_n}{a'_c} \right) \left( \frac{L_n}{c} \right) \right] \\ &\cong \frac{1}{f_n \varphi_n} \sum_a \left[ (a'_c \cdot c)^{\varphi_n} - a^{\varphi_n} \right] \left( \frac{L_n}{a} \right). \end{aligned}$$

**Lemma 7.1.** *We have  $(a'_c \cdot c)^{\varphi_n} - a^{\varphi_n} \equiv 0 \pmod{f_n \varphi_n}$ .*

*Proof.* By definition,  $a'_c \cdot c = a + \lambda_a^n(c) f_n$  with  $\lambda_a^n(c) \in \mathbb{Z}$ . Consider:

$$\begin{aligned} A &:= \frac{(a'_c \cdot c)^{\varphi_n} - a^{\varphi_n}}{f_n \varphi_n} \\ &= \frac{[a^{\varphi_n} + \lambda_a^n(c) f_n \varphi_n a^{\varphi_n-1} + \lambda_a^n(c)^2 f_n^2 \frac{\varphi_n(\varphi_n-1)}{2} a^{\varphi_n-2} + \dots] - a^{\varphi_n}}{f_n \varphi_n} \\ &\equiv \lambda_a^n(c) a^{\varphi_n-1} + \lambda_a^n(c)^2 f_n \frac{(\varphi_n-1)}{2} a^{\varphi_n-2} \\ &\equiv \lambda_a^n(c) a^{\varphi_n-1} \equiv \lambda_a^n(c) a^{-1} \pmod{p^{n+1}}, \end{aligned}$$

since  $a^{\varphi_n} \equiv 1 \pmod{qp^n}$ .

When  $p = 2$ , one must take into account the term  $\lambda_a^n(c) f_n \frac{\varphi_n-1}{2} a^{\varphi_n-2} \sim \frac{1}{2} \lambda_a^n(c) f_n$ , in which case the congruence is with the modulus  $p^{n+1}$  (which is sufficient since for  $n \geq n_0 + e$ , this modulus annihilates  $\mathcal{T}_K$  for any  $p$ ).  $\square$

We have obtained for all  $n \geq n_0 + e$ :

$$(7.2) \quad \mathcal{A}_{L_n}(c) \cong \sum_{a=1}^{f_n} \lambda_a^n(c) \cdot a^{-1} \left( \frac{L_n}{a} \right) \cong \mathcal{S}_{L_n}(c)^*,$$

thus giving again, by restriction to  $K$ , the annihilator  $\mathcal{A}_{K,n}(c) \in \mathbb{Z}_p[G_K]$  of

$$\mathcal{T}_K \text{ such that (for all } n \geq n_0 + e) \mathcal{A}_{K,n}(c) \cong \sum_{a=1}^{f_n} \lambda_a^n(c) a^{-1} \left( \frac{K}{a} \right).$$

## 7.2. Normic properties of the $\mathcal{A}_{L_n}$ – Euler factors.

**Theorem 7.2.** [13, Proposition II.2 (iv)]. *Let  $K$  be of conductor  $f = m\ell$  where  $m$  is the conductor of a subfield  $k$  of  $K$  and where  $\ell \neq p$  is a prime number. For  $n \geq n_0$ , let  $L_n := K(\mu_{qp^n})$  and the analogous field  $l_n$  for  $k$ , of conductors  $f_n$  and  $m_n$ , respectively; recall that  $\varphi_n = \varphi(qp^n)$ .*

Let  $\mathcal{A}_{L_n} := \frac{-1}{f_n \varphi_n} \sum_{a=1}^{f_n} a^{\varphi_n} \left( \frac{L_n}{a} \right)$  and  $\mathcal{A}_{l_n} := \frac{-1}{m_n \varphi_n} \sum_{b=1}^{m_n} b^{\varphi_n} \left( \frac{l_n}{b} \right)$ . Then:

$$N_{L_n/l_n}(\mathcal{A}_{L_n}) \cong \left( 1 - \ell^{\varphi_n} \frac{1}{\ell} \left( \frac{l_n}{\ell} \right) \right) \mathcal{A}_{l_n}, \quad \text{resp.,} \quad N_{L_n/l_n}(\mathcal{A}_{L_n}) \cong \mathcal{A}_{l_n},$$

if  $\ell \nmid m$ , resp.,  $\ell \mid m$  (modulo  $p^{n+1} \mathbb{Z}_p[G_n] + (1 - s_\infty) \mathbb{Z}_p[G_n]$ ).

*Proof.* Suppose first that  $\ell \nmid m$ , so  $f_n = l m_n$ .<sup>2</sup> Put  $a = b + \lambda m_n$ ,  $\lambda \in [0, \ell-1]$ ,  $b \in [1, m_n]$  prime to  $m_n$ ; since  $a \in [1, f_n]$  is prime to  $f_n$ ,  $b$  is prime to  $m_n$  and  $\lambda \neq \lambda_b^*$  such that  $b + \lambda_b^* m_n =: b'_\ell \cdot \ell$ ,  $b'_\ell \in \mathbb{Z}$ . Thus  $a^{\varphi_n} = (b + \lambda m_n)^{\varphi_n} \equiv b^{\varphi_n} + b^{\varphi_n-1} \lambda m_n \varphi_n \pmod{m_n \varphi_n p^{n+1}}$ . Then:

$$\begin{aligned} N_{L_n/l_n}(\mathcal{A}_{L_n}) &\cong \frac{-1}{\ell m_n \varphi_n} \cdot \sum_{b, \lambda \neq \lambda_b^*} \left[ b^{\varphi_n} + b^{\varphi_n-1} \lambda m_n \varphi_n \right] \left( \frac{l_n}{b} \right) \\ &\cong \frac{-(\ell-1)}{\ell m_n \varphi_n} \sum_b b^{\varphi_n} \left( \frac{l_n}{b} \right) - \frac{1}{\ell} \sum_{b, \lambda \neq \lambda_b^*} b^{\varphi_n-1} \lambda \left( \frac{l_n}{b} \right) \end{aligned}$$

<sup>2</sup>For  $\ell = 2$  and  $m$  odd,  $f = 2m$  is not a conductor stricto sensu, but the following computations are exact and necessary with the modulus  $m_n$  and  $f_n = 2m_n$ ; then if  $f = 2^k \cdot m$  ( $m$  odd,  $k \geq 2$ ), the second case of the theorem applies and shall give the Euler factor  $(1 - 2^{\varphi_n} \frac{1}{2} (\frac{l_n}{2})) \cong (1 - \frac{1}{2} (\frac{l_n}{2}))$ . If  $p \mid f$  and  $p \nmid m$ , there is no Euler factor for  $p$  since  $m_n$  and  $f_n$  are divisible by  $p$ ; in other words, these computations and the forthcoming ones are, by nature, not “primitive” at  $p$ .

$$\begin{aligned}
&\cong \left(1 - \frac{1}{\ell}\right) \mathcal{A}_{l_n} - \frac{1}{\ell} \sum_{b, \lambda \neq \lambda_b^*} b^{\varphi_n-1} \lambda \left(\frac{l_n}{b}\right) \\
&\cong \left(1 - \frac{1}{\ell}\right) \mathcal{A}_{l_n} - \frac{1}{\ell} \sum_b b^{\varphi_n-1} \left(\frac{l_n}{b}\right) \left(\sum_{\lambda \neq \lambda_b^*} \lambda\right) \\
&\cong \left(1 - \frac{1}{\ell}\right) \mathcal{A}_{l_n} - \frac{1}{\ell} \sum_b b^{\varphi_n-1} \left(\frac{l_n}{b}\right) \left(\frac{\ell(\ell-1)}{2} - \lambda_b^*\right).
\end{aligned}$$

We remark that  $\lambda_b^* = \lambda_b^n(\ell)$  is relative to the writing  $b'_\ell \cdot \ell = b + \lambda_b^n(\ell) m_n$  and that  $b^{\varphi_n-1} \equiv b^{-1} \pmod{p^{n+1}}$ , whence using  $\sum_b b^{-1} \left(\frac{l_n}{b}\right) \cong 0$ :

$$\mathrm{N}_{L_n/l_n}(\mathcal{A}_{L_n}) \cong \left(1 - \frac{1}{\ell}\right) \mathcal{A}_{l_n} + \frac{1}{\ell} \sum_b \lambda_b^* \cdot b^{-1} \left(\frac{l_n}{b}\right).$$

But as we know (see relations 7.1 and (7.2)),  $\sum_b \lambda_b^* b^{-1} \left(\frac{l_n}{b}\right) \cong \mathcal{A}_{l_n}(\ell)$ ; so:

$$\mathrm{N}_{L_n/l_n}(\mathcal{A}_{L_n}) \cong \left(1 - \frac{1}{\ell}\right) \mathcal{A}_{l_n} + \frac{1}{\ell} \mathcal{A}_{l_n}(\ell);$$

since  $\mathcal{A}_{l_n}(\ell) \cong \left(1 - \ell^{\varphi_n} \left(\frac{l_n}{\ell}\right)\right) \mathcal{A}_{l_n}$ , we get  $\mathrm{N}_{L_n/l_n}(\mathcal{A}_{L_n}) \cong \left(1 - \ell^{\varphi_n} \frac{1}{\ell} \left(\frac{l_n}{\ell}\right)\right) \mathcal{A}_{l_n}$ .

The case  $\ell \mid m$  is obtained easily from the same computations.  $\square$

Of course, for all  $h \geq 0$  we get:

$$\mathrm{N}_{L_{n+h}/L_n}(\mathcal{A}_{L_{n+h}}) \cong \mathcal{A}_{L_n},$$

which expresses the coherence of the family  $(\mathcal{A}_{L_n})_n$  in the cyclotomic tower.

**Corollary 7.3.** (i) Let  $K/k$  be an extension of fields of conductors  $f_K$  and  $f_k$ , respectively. Multiplying by  $\left[1 - c^{\varphi_n} \left(\frac{l_n}{c}\right)\right] = \mathrm{N}_{L_n/l_n} \left[1 - c^{\varphi_n} \left(\frac{L_n}{c}\right)\right]$  to get elements in the algebras  $(\mathbb{Z}/p^{n+1}\mathbb{Z})[\mathrm{Gal}(L_n/\mathbb{Q})]$  and  $(\mathbb{Z}/p^{n+1}\mathbb{Z})[\mathrm{Gal}(l_n/\mathbb{Q})]$ , one obtains  $\mathrm{N}_{L_n/l_n}(\mathcal{A}_{L_n}(c)) \cong \prod_{\ell \mid f_K, \ell \nmid p f_k} \left(1 - \frac{1}{\ell} \left(\frac{l_n}{\ell}\right)\right) \mathcal{A}_{l_n}(c)$ .

(ii) Let  $\mathcal{A}_{K,n}(c)$  and  $\mathcal{A}_{k,n}(c)$  be the restrictions of  $\mathcal{A}_{L_n}(c)$  and  $\mathcal{A}_{l_n}(c)$  to  $K$  and  $k$ , respectively; then  $\mathrm{N}_{K/k}(\mathcal{A}_{K,n}(c)) \cong \prod_{\ell \mid f_K, \ell \nmid p f_k} \left(1 - \frac{1}{\ell} \left(\frac{k}{\ell}\right)\right) \cdot \mathcal{A}_{k,n}(c)$ .

(iii) The family  $(\mathcal{A}_{K,n})_n = (\mathrm{N}_{L_n/K}(\mathcal{A}_{L_n}))_n$  defines a pseudo-measure denoted  $\mathcal{A}_K$  by abuse, such that the coherent family  $(\mathcal{A}_{K,n}(c))_n$  defines the element  $\mathcal{A}_K(c) = \left(1 - \left(\frac{K}{c}\right)\right) \cdot \mathcal{A}_K \in \mathbb{Z}_p[G_K]$  and gives the main formula:

$$\mathrm{N}_{K/k}(\mathcal{A}_K(c)) \cong \prod_{\ell \mid f_K, \ell \nmid p f_k} \left(1 - \frac{1}{\ell} \left(\frac{k}{\ell}\right)\right) \cdot \mathcal{A}_k(c).$$

*Remarks 7.4.* (i) In a numerical point of view, we shall write (e.g., for  $n = e$  when  $K \cap \mathbb{Q}_\infty = \mathbb{Q}$ )

$$\mathcal{A}_{K,n}(c) \cong \sum_{\sigma \in G_K} \left( \sum_{a, \left(\frac{K}{a}\right) = \sigma} \lambda_a^n(c) a^{-1} \right) \cdot \sigma =: \sum_{\sigma \in G_K} \Lambda_\sigma^n(c) \cdot \sigma.$$

Then the next step shall be to interpret the limit,  $\Lambda_\sigma(c)$ , of the coefficients  $\Lambda_\sigma^n(c) = \sum_{a, \left(\frac{K}{a}\right) = \sigma} \lambda_a^n(c) a^{-1}$ , for  $n \rightarrow \infty$ , giving an equivalent annihilator, but with a more canonical interpretation.

(ii) As we know, in [12, 13, 21, 25, 27, 28, 5, 18, 26, 20, 1, 2, 4], similar limits are given by  $p$ -adic logarithms of cyclotomic numbers/units of  $\mathbb{Q}^f$  as an expression of the values at  $s = 1$  of the  $p$ -adic  $L$ -functions of  $K$ .

(iii) In the relation  $\mathcal{A}_K(c) := \left[1 - \left(\frac{K}{c}\right)\right] \mathcal{A}_K$ , the choice of  $c$  must be such that the integers  $1 - \chi(c)$  be of minimal  $p$ -adic valuation for the characters  $\chi$  of  $K$ . But  $1 - \chi(c)$  is invertible if and only if  $\chi(c)$  is not a root of unity of  $p$ -power order.

(iv)  $N_{K/\mathbb{Q}}(\mathcal{A}_{K,n}(c)) \rightarrow 0$  ( $p$ -adically) as  $n \rightarrow \infty$ ; whence  $N_{K/\mathbb{Q}}(\mathcal{A}_K(c)) = 0$ .

## 8. REMARKS ABOUT SOLOMON'S ANNIHILATORS

We shall give two examples: one giving the same annihilator as our's, and another giving a Solomon annihilator in part degenerated, contrary to  $\mathcal{A}_K(c)$ .

**8.1. Cubic field of conductor 1381 and Solomon's  $\Psi_K$ ,  $p = 7$ .** We have (see the previous table of § 5.3)  $P = x^3 + x^2 - 460x - 1739$  and the classical program gives the class number, the group structure of  $\mathcal{T}_K$  (in  $L$ ) and the units:

```
{P=x^3+x^2-460*x-1739;K=bnfinit(P,1);p=7;nt=8;Kpn=bnrinit(K,p^nt);r=1;
Hpn=component(component(Kpn,5),2);C8=component(K,8);E=component(C8,5);
h=component(component(C8,1),1);L=listcreate;i=component(matsize(Hpn),2);
R=0;for(k=1,i-1,c=component(Hpn,i-k+1);if(Mod(c,p)==0,R=R+1;
listinsert(L,p^valuation(c,p),1));print(L);print("h=",h," ",L," E=",E)}
```

h=1 List([343, 7])

E=[245/13\*x^2 - 4606/13\*x - 21522/13, 147/13\*x^2 + 3479/13\*x + 11272/13]

So, the class group is trivial,  $\mathcal{T}_K = \mathcal{R}_K \simeq \mathbb{Z}/7^3\mathbb{Z} \times \mathbb{Z}/7\mathbb{Z}$  and the cyclotomic units are the fundamental units. Then we shall use a definition of the automorphism  $\sigma$  to define the Galois operation on the units:

```
{P=x^3 + x^2 - 460*x - 1739;print(nfgaloisconj(P))}
[x, -1/13*x^2 - 2/13*x + 302/13, 1/13*x^2 - 11/13*x - 315/13]
```

From  $\varepsilon = \frac{245}{13}x^2 - \frac{4606}{13}x - \frac{21522}{13}$  and  $\sigma : x \mapsto -\frac{1}{13}x^2 - \frac{2}{13}x + \frac{302}{13}$ , one gets:

```
Mod(245/13*(-1/13*x^2 - 2/13*x + 302/13)^2 -
4606/13*(-1/13*x^2 - 2/13*x + 302/13) - 21522/13,P)=
Mod(147/13*x^2 + 3479/13*x + 11259/13, x^3 + x^2 - 460*x - 1739)
```

which is  $\varepsilon^\sigma$  and the units are, on the  $\mathbb{Q}$ -base  $\{1, x, x^2\}$ :

$$\begin{aligned} \varepsilon &= \varepsilon_1 = \frac{245}{13}x^2 - \frac{4606}{13}x - \frac{21522}{13}, \\ \varepsilon^\sigma &= \varepsilon_2 = \frac{147}{13}x^2 + \frac{3479}{13}x + \frac{11259}{13}, \\ \varepsilon^{\sigma^2} &= \varepsilon_3 = -\frac{392}{13}x^2 + \frac{1127}{13}x + \frac{175948}{13}. \end{aligned}$$

The second unit given by PARI is  $\frac{147}{13}x^2 + \frac{3479}{13}x + \frac{11272}{13} = -\varepsilon^{-\sigma^2}$ . The order of  $\varepsilon$  modulo  $p = 7$  is 114. We compute  $A_i := \varepsilon_i^{114}$  modulo  $7^6$ ,  $i = 1, 2, 3$ , then  $L_i := A_i - 1$ :

```
{P=x^3+x^2-460*x-1739;
E1=Mod(245/13*x^2-4606/13*x-21522/13,P+Mod(0,7^6));
E2=Mod(147/13*x^2+3479/13*x+11259/13,P+Mod(0,7^6));
E3=Mod(-392/13*x^2+1127/13*x+175948/13,P+Mod(0,7^6));
L1=E1^114-1;L2=E2^114-1;L3=E3^114-1;
print(lift(L1)," ",lift(L2)," ",lift(L3))}
```

$$L_1 = 17542x^2 + 48608x + 81879 = 7^2(358x^2 + 992x + 1671) = 7^2\alpha_1,$$

$$L_2 = 62867x^2 + 833x + 33761 = 7^2(1283x^2 + 17x + 689) = 7^2\alpha_2,$$

$$L_3 = 37240x^2 + 68208x + 2009 = 7^2(760x^2 + 1392x + 41) = 7^2\alpha_3,$$

giving  $\frac{1}{7}\log(\varepsilon_i) \equiv 7\alpha_i - \frac{1}{2}7^3\alpha_i^2 \pmod{7^4}$ :

$$\frac{1}{7}\log(\varepsilon) \equiv 791x^2 + 2142x + 378 = 7(113x^2 + 306x + 54) \pmod{7^4},$$

$$\frac{1}{7}\log(\varepsilon^\sigma) \equiv 2121x^2 + 119x + 364 = 7(303x^2 + 17x + 52) \pmod{7^4},$$

$$\frac{1}{7}\log(\varepsilon^{\sigma^2}) \equiv 1890x^2 + 140x + 1659 = 7(270x^2 + 20x + 237) \pmod{7^4}.$$

So, the Solomon annihilator  $\frac{1}{p} \sum_{\sigma \in G_K} \log(\varepsilon^\sigma) \cdot \sigma^{-1}$  of  $\mathcal{T}_K$  is (modulo  $7^3$  and up to a 7-adic unit):

$$\Psi_K \equiv 7 \cdot [15x^2 + 12x + 5 + (9x^2 + 17x + 3)\sigma^{-1} + (25x^2 + 20x + 41)\sigma^{-2}].$$

Since the norm is a trivial annihilator, we can replace  $\Psi_K$  by

$$\begin{aligned} \Psi'_K &= \Psi_K - 7 \cdot (15x^2 + 12x + 5)(1 + \sigma^{-1} + \sigma^{-2}) \\ &\equiv 7 \cdot [(43x^2 + 5x + 47)\sigma^{-1} + (10x^2 + 8x + 36)]\sigma^{-2} \pmod{7^3}. \end{aligned}$$

Then,  $43x^2 + 5x + 47$  is invertible  $p$ -adically (its norm is prime to 7) which gives the equivalent annihilator:

$$7 \cdot [\sigma + (10x^2 + 8x + 36) \cdot (43x^2 + 5x + 47)^{-1}] \equiv \sigma + 31 \pmod{7^2}$$

equivalent to the annihilator defined by  $7 \cdot (\sigma - 18)$  modulo  $7^3$ .

Our annihilator, given by the previous table, is  $1738 + 2186\sigma^{-1} + 2361\sigma^{-2}$  equivalent to  $448 + 623\sigma \equiv 7 \cdot (\sigma - 18) \pmod{7^3}$ .

So  $\sigma - 18$  is an annihilator for the submodule  $\mathcal{T}_K^7 \simeq \mathbb{Z}/7^2\mathbb{Z}$ , which is coherent since 18 is of order 3 modulo  $7^3$ .

The perfect identity of the two results shows that no information has been lost for this particular case, whatever the method (but in the case of cyclic fields of prime degree, there is not any Euler factor).

## 8.2. Cyclic quartic field of conductor $37 \cdot 45161$ and Solomon's $\Psi_K$ .

Let  $K$  be a real cyclic quartic field of conductor  $f$  such that the quadratic subfield  $k$  has conductor  $m \mid f$ , with for instance  $f = \ell m$ ,  $\ell$  prime split in  $k/\mathbb{Q}$ . We take  $p \equiv 1 \pmod{4}$ ,  $p \nmid f$ .

Put  $\eta_f := 1 - \zeta_f$ ,  $\eta_m := 1 - \zeta_m$ ,  $\eta_K := N_{\mathbb{Q}^f/K}(\eta_f)$ ,  $\eta_k := N_{\mathbb{Q}^m/k}(\eta_m)$ .

Then we have the Solomon annihilator:

$$\Psi_K = \frac{1}{p} \sum_{\sigma \in G_K} \log(\eta_K^\sigma) \cdot \sigma^{-1}.$$

Since, from the formula (4.2), one has  $N_{\mathbb{Q}^f/\mathbb{Q}^m}(\eta_f) = \eta_m^{(1 - (\frac{\mathbb{Q}^m}{\ell})^{-1})}$ , i.e.,

$N_{K/k}(\eta_K) = \eta_k^{(1 - (\frac{k}{\ell})^{-1})} = 1$ , we get (with  $G_K = \{1, \sigma, \sigma^2, \sigma^3\}$ ):

$$\begin{aligned} \Psi_K &= \frac{1}{p} (\log(\eta_K) + \log(\eta_K^\sigma) \cdot \sigma^{-1} + \log(\eta_K^{\sigma^2}) \cdot \sigma^{-2} + \log(\eta_K^{\sigma^3}) \cdot \sigma^{-3}) \\ &= \frac{1}{p} (\log(\eta_K) + \log(\eta_K^\sigma) \cdot \sigma^{-1} - \log(\eta_K) \cdot \sigma^{-2} - \log(\eta_K^\sigma) \cdot \sigma^{-3}) \end{aligned}$$

So, in this particular situation, one has:

$$(8.1) \quad \Psi_K = \frac{1}{p} (\log(\eta_K) + \log(\eta_K^\sigma) \cdot \sigma^{-1}) \cdot (1 - \sigma^2).$$

Suppose that  $\mathcal{T}_K$  is equal to the transfer of  $\mathcal{T}_k$  (many examples are available), then  $\mathcal{T}_K$  is annihilated by  $(1 - \sigma^2)$ , whatever the structure of  $\mathcal{T}_k \simeq \mathcal{T}_K$ .



For instance, define  $K$  by  $x = \sqrt{\ell \sqrt{m} \frac{\sqrt{m} + a}{2}}$  where  $m = a^2 + b^2$ ,  $b = 2b'$ . This gives the polynomial  $P = x^4 - \ell m x^2 + \ell^2 m b'^2$ . The following program gives many examples with non-trivial  $\mathcal{T}_k$  (with  $m$  prime,  $p = 5$ ):

```
{p=5;forprime(m=1,10^5,if(Mod(m,20)!=1,next);P=x^2-m;K=bnfinit(P,1);nt=12;
Kpn=bnrinit(K,p^nt);Hpn=component(component(Kpn,5),2);L=listcreate;
i=component(matsize(Hpn),2);R=0;for(k=1,i-1,c=component(Hpn,i-k+1);
if(Mod(c,p)==0,R=R+1;listinsert(L,p^valuation(c,p),1));if(R>0,
print("m=",m," structure",L)))}
```

For  $m = 45161$ , one obtains  $\mathcal{T}_k \simeq \mathbb{Z}/5^5\mathbb{Z}$ ; then  $a = 205$ ,  $b' = 28$ . Now we find some primes  $\ell$  with the following program:

```
{p=5;m=45161;bprim=28;forprime(ell=7,10^3,if(Mod(ell,4)!=1,next);
if(kronecker(m,ell)!=1,next);P=x^4-ell*m*x^2+ell^2*m*bprim^2;
K=bnfinit(P,1);nt=12;Kpn=bnrinit(K,p^nt);Hpn=component(component(Kpn,5),2);
L=listcreate;i=component(matsize(Hpn),2);R=0;
for(k=1,i-1,c=component(Hpn,i-k+1);if(Mod(c,p)==0,R=R+1;
listinsert(L,p^valuation(c,p),1));
print("ell=",ell," m=",m," P=",P," structure",L))}
```

giving the following examples (for which  $\mathcal{T}_k$  is a direct factor in  $\mathcal{T}_K$ ):

```
ell=13 P=x^4-587093*x^2+5983651856 structure [3125]
ell=17 P=x^4-767737*x^2+10232398736 structure [3125,5,5]
ell=37 P=x^4-1670957*x^2+48471120656 structure [3125]
ell=997 P=x^4-45025517*x^2+35194105312016 structure [3125,25]
```

We consider the case  $\ell = 37$ ,  $P = x^4 - 1670957x^2 + 48471120656$  for which PARI gives the following information that may be used by the reader:

```
nfgaloisconj(x^4-1670957*x^2+48471120656)=
[-x, x, -1/212380*x^3 + 43593/5740*x, 1/212380*x^3 - 43593/5740*x]
```

```
{P=x^4-1670957*x^2+48471120656;K=bnfinit(P,1);p=5;nt=8;Kpn=bnrinit(K,p^nt);
r=1; Hpn=component(component(Kpn,5),2);C8=component(K,8);E=component(C8,5);
h=component(component(C8,1),1);L=listcreate;i=component(matsize(Hpn),2);R=0;
for(k=1,i-1,c=component(Hpn,i-k+1);if(Mod(c,p)==0,R=R+1;
listinsert(L,p^valuation(c,p),1));print("h=",h," ",L);print("E=",E)}
```

```
h=2 List([3125])
```

Now, consider the annihilator  $\mathcal{A}_{K,n}(c) =: A_K$ ; since  $\mathcal{T}_K \simeq \mathcal{T}_k$ , we get  $\mathcal{T}_K^{A_K} \simeq \mathcal{T}_k^{N_{K/k}(A_K)}$ , where (see Corollary 7.3):

$$N_{K/k}(\mathcal{A}_{K,n}(c)) \cong \left(1 - \frac{1}{\ell} \left(\frac{k}{\ell}\right)\right) \mathcal{A}_{k,n}(c).$$

Then  $\ell = 37 \equiv 2 \pmod{5}$  splits in  $k$  and  $1 - \frac{1}{\ell} \left(\frac{k}{\ell}\right) = 1 - \frac{1}{\ell}$  is invertible.

So  $A_K$  acts on  $\mathcal{T}_K$  as  $\mathcal{A}_{k,n}(c)$  on  $\mathcal{T}_k$ ; we can use the program for quadratic fields and  $p > 2$  (of course the bounds  $bf, Bf$  may be arbitrary):

```
{p=5;nt=8;bf=45161;Bf=45161;for(f=bf,Bf,v=valuation(f,2);M=f/2^v;
if(core(M)!=M,next);if((v==1||v>3)|| (v==0 & Mod(M,4)!=1)||
(v==2 & Mod(M,4)==1),next);P=x^2-f;K=bnfinit(P,1);Kpn=bnrinit(K,p^nt);
C5=component(Kpn,5);Hpn0=component(C5,1);Hpn=component(C5,2);
h=component(component(component(K,8),1),2);L=listcreate;ex=0;
i=component(matsize(Hpn),2);R=0;for(k=1,i-1,co=component(Hpn,i-k+1);
if(Mod(co,p)==0,R=R+1;val=valuation(co,p);if(val>ex,ex=val);
listinsert(L,p^val,1));Hpn1=component(Hpn,1);
vptor=valuation(Hpn0/Hpn1,p);tor=p^vptor;S0=0;S1=0;pN=p*p^ex;fn=pN*f;
```

```

for(cc=2,10^2,if(gcd(cc,p*f)!=1 || kronecker(f,cc)!=-1,next);c=cc;break);
for(a=1,fn/2,if(gcd(a,fn)!=1,next);asurc=lift(a*Mod(c,fn)^-1);
lambda=(asurc*c-a)/fn;u=Mod(lambda*a^-1,pN);
s=kronecker(f,a);if(s==1,S0=S0+u);if(s==-1,S1=S1+u));
L0=lift(S0);L1=lift(S1);A=L1-L0;if(A!=0,A=p^valuation(A,p));
print(f," P=",P," ",L0," ",L1," A=",A," tor=",tor," T_K=",L," Cl_K=",h))}

```

giving the annihilator  $A_k \equiv 10185 + 3935\bar{\sigma} \pmod{5^6}$  where  $\bar{\sigma}$  generates the Galois group of  $k/\mathbb{Q}$ ; then,  $A_k$  is equivalent, modulo the norm, to the integer  $10185 - 3935 \equiv 2 \cdot 5^5 \pmod{5^6}$ , which is perfect since  $\mathcal{T}_k \simeq \mathbb{Z}/5^5\mathbb{Z}$ .

The class group of  $k$  being trivial, the fundamental unit  $\varepsilon$  is the cyclotomic one and is such that  $\varepsilon^4 = 1 + 5^6 \cdot \alpha$ ,  $\alpha$  prime to 5, which confirm that:

$$(8.2) \quad \Psi_k \sim \frac{1}{5}(\log(\varepsilon) + \log(\varepsilon^{\bar{\sigma}}) \cdot \bar{\sigma}) = \frac{1}{5}\log(\varepsilon)(1 - \bar{\sigma})$$

equivalent (modulo the norm) to  $\frac{2}{5}\log(\varepsilon)$  as expected.

## 9. ABOUT THE ANNIHILATOR $\mathcal{A}_K(c)$ AND THE PRIMITIVE $L_p(1, \chi)$

**9.1. Galois characters v.s. Dirichlet characters.** Let  $f_K$  be the conductor of  $K$ . In most formulas, the characters  $\chi$  of  $K$  must be primitive of conductor  $f_\chi \mid f_K$ , whence Dirichlet characters on  $(\mathbb{Z}/f_\chi\mathbb{Z})^\times$  such that  $\chi\left[\left(\frac{\mathbb{Q}^{f_\chi}}{a}\right)\right]$  makes sense for  $a \in \mathbb{Z}$ , prime to  $f_\chi$  but not necessarily for  $\chi\left[\left(\frac{\mathbb{Q}^{f_K}}{a}\right)\right]$  if a prime  $\ell$  divides both  $a$  and  $f_K$  but not  $f_\chi$ . This is an obstruction to consider them as Galois characters over  $\mathbb{Z}_p[G_K]$  for instance, whence defined on  $(\mathbb{Z}/f_K\mathbb{Z})^\times$ ; so we shall introduce the corresponding Galois character of  $G_K$ , denoted  $\psi_\chi =: \psi$ . A Galois character  $\psi$  of  $G_K$  is also a character of  $G_n = \text{Gal}(L_n/\mathbb{Q})$  whose kernel fixes  $K$ , so  $\psi(a)$  ( $a \in [1, f_n]$  prime to  $f_n$ ) is the image by  $\psi$  of the Artin symbol  $\left(\frac{L_n}{a}\right)$  whence of  $\left(\frac{K}{a}\right)$ .

Any non-primitive writing  $\psi(\mathcal{A}_K)$ , for  $\mathcal{A}_K \in \mathbb{Z}_p[G_K]$ , may introduce a product of Euler factors. Indeed, let  $k_\chi = k_\psi$  be the subfield fixed by the kernel of  $\psi$  (then  $\chi$  is a primitive character of  $k_\chi$  but not necessarily of  $K$ ); then,  $\psi(\mathcal{A}_K) = \psi(N_{K/k_\chi}(\mathcal{A}_K)) = \chi(\mathcal{E}_{k_\chi}) \cdot \chi(\mathcal{A}_{k_\chi})$  in which  $\chi(\mathcal{E}_{k_\chi})$  may be non-invertible (or 0).

**9.2. Expression of  $\psi(\mathcal{A}_K(c))$ .** Let  $\psi$  be any Galois character of  $K$  considered as Galois character of  $\text{Gal}(L_n/\mathbb{Q})$ , for  $n \geq n_0 + e$ . We then have the following result about the computation of the annihilator  $\mathcal{A}_K(c)$  (cf. Theorem 5.5), without any hypothesis on  $K$  and  $p$ :

**Lemma 9.1.** *The expression  $\psi(\mathcal{A}_K(c))$  is the product of the multiplier  $1 - \psi\left(\left(\frac{L_\infty}{c}\right)\right)$  by the non-primitive value  $L_p(1, \psi)$ . In other words, one has:*

$$\begin{aligned} \psi(\mathcal{A}_K(c)) &= \sum_{\sigma \in G_K} \Lambda_\sigma(c) \psi(\sigma) = (1 - \psi(c))L_p(1, \psi) \\ &= (1 - \psi(c)) \prod_{\ell \mid f_K, \ell \nmid p f_\chi} (1 - \chi(\ell)\ell^{-1})L_p(1, \chi). \end{aligned}$$

*Proof.* From [13, Propositions II.2, II.3, Définition II.3, II.4, and Remarques II.3, II.4], then [7, page 292], we obtain, using the computations of the § 7.1, the link between the limit:

$$\psi(\mathcal{A}_K(c)) = \sum_{\sigma \in G_K} \Lambda_\sigma(c) \cdot \psi(\sigma) \quad (\text{cf. Remark 7.4 (i)}),$$

for  $n \rightarrow \infty$ , of  $\psi(\mathcal{A}_{L_n}(c)) = \psi(\mathcal{A}_{K,n}(c)) = \sum_{\sigma \in G_K} \Lambda_{\sigma}^n(c) \psi(\sigma)$  and the value at  $s = 1$  of the  $L_p$ -function of the *primitive character*  $\chi$  associated to  $\psi$ .  $\square$

*Remark 9.2.* Note that in the various calculations in § 7.1,  $\varphi_n = \varphi(qp^n)$  when  $n \rightarrow \infty$  plays the role of  $1 - s$  when  $s \rightarrow 1$  in the construction of  $p$ -adic  $L_p$ -functions by reference to Bernoulli numbers.

For all primitive Dirichlet character  $\chi \neq 1$  of  $K$ , of modulus  $f_{\chi}$  (or  $pf_{\chi}$  if  $p \nmid f_{\chi}$ ), and for all  $p \geq 2$ , we have the classical formulas of the value at  $s = 1$  of the  $p$ -adic  $L$ -functions (see for instance [29, Theorem 5.18]), where  $\tau(\chi) = \sum_{(a, f_{\chi})=1} \chi(a) \zeta_{f_{\chi}}^a$  is the primitive Gauss sum of  $\chi$ :

$$L_p(1, \chi) = -\left(1 - \frac{\chi(p)}{p}\right) \cdot \frac{\tau(\chi)}{f_{\chi}} \sum_{a \in [1, f_{\chi}], (a, f_{\chi})=1} \chi^{-1}(a) \log(1 - \zeta_{f_{\chi}}^a),$$

where the Euler factor  $1 - \chi(p)p^{-1}$  illustrates the fact that for  $L_p$ -functions, any character  $\chi$  is considered modulo  $pf_{\chi}$  when  $p \nmid f_{\chi}$ .

From the Coates formula [6] and classical computations (see also some details in [11, § 2.2]) we recall that  $\#\mathcal{T}_K \sim \prod_{\chi \neq 1} \frac{1}{2} L_p(1, \chi)$  (up to a  $p$ -adic unit).

Moreover, we know that in the semi-simple case, one obtains the orders of the isotypic components of  $\mathcal{T}_K$  by means of the  $\frac{1}{2} L_p(1, \chi)$ .

*Remark 9.3.* Let  $\chi$  be a primitive Dirichlet character of conductor  $f_{\chi}$ . We define the “modified Solomon element” of  $\mathbb{Z}_p[G_{k_{\chi}}]$ :

$$\Psi_{k_{\chi}} := -\left(1 - \frac{\chi(p)}{p}\right) \cdot \frac{\tau(\chi)}{f_{\chi}} \sum_{\tau \in G_{k_{\chi}}} \log(\eta_{k_{\chi}}^{\tau}) \cdot \tau^{-1}.$$

Whence  $L_p(1, \chi) = \chi(\Psi_{k_{\chi}})$  ( $\chi \neq 1$  primitive). Put  $C_{\chi} := -\left(1 - \frac{\chi(p)}{p}\right) \cdot \frac{\tau(\chi)}{f_{\chi}}$ . When  $p \nmid f_{\chi}$ ,  $\tau(\chi)$  is invertible and  $C_{\chi} \cdot \log(\eta_{k_{\chi}}^{\tau}) \sim \frac{1}{p} \cdot \log(\eta_{k_{\chi}}^{\tau}) \sim \Psi_{k_{\chi}}$  (the original Solomon element); when  $p \mid f_{\chi}$ , the factor  $\frac{1}{p}$  in  $C_{\chi}$  is replaced, ahead the logarithms, by the quotient  $\frac{1}{\tau(\chi)}$  having the suitable  $p$ -valuations. For instance, if  $d$  is prime and  $p$  unramified,  $\frac{1}{p} \sum_{\sigma \in G_K} \log(\eta_K^{\sigma}) \cdot \sigma^{-1}$  annihilates  $\mathcal{T}_K$ .

**9.3. The annihilator  $\mathcal{A}_K(c)$  and the  $\Psi_{k_{\chi}}$ .** The following statement does not assume any hypothesis on  $K$  and  $p$  and gives again the known results of annihilation (e.g., semi-simple case).

**Theorem 9.4.** *Let  $K$  be a real abelian number field, of degree  $d$ , of Galois group  $G_K$  and of conductor  $f_K$ . Let  $\mathcal{A}_K(c) = \lim_{n \rightarrow \infty} \mathcal{A}_{K,n}(c) \in \mathbb{Z}_p[G_K]$  annihilating  $\mathcal{T}_K$  (cf. Theorem 5.5). Then we have (where each  $\chi$  is the primitive Dirichlet character associated to the Galois character  $\psi$  of  $G_K$ ):*

$$\mathcal{A}_K(c) = \frac{1}{d} \sum_{\sigma \in G_K} \left[ \sum_{\psi} \psi^{-1}(\sigma)(1 - \psi(c)) \cdot \prod_{\ell \mid f_K, \ell \nmid pf_{\chi}} \left(1 - \frac{\chi(\ell)}{\ell}\right) \cdot \chi(\Psi_{k_{\chi}}) \right] \cdot \sigma,$$

with  $\Psi_{k_{\chi}} = -\left(1 - \frac{\chi(p)}{p}\right) \frac{\tau(\chi)}{f_{\chi}} \sum_{\tau \in G_{k_{\chi}}} \log(N_{\mathbb{Q}^{f_{\chi}}/k_{\chi}}(1 - \zeta_{f_{\chi}})^{\tau}) \cdot \tau^{-1}$ .

Thus,  $\mathcal{T}_K$  is annihilated by the ideal  $\mathfrak{A}_K$  of  $\mathbb{Z}_p[G_K]$  generated by the  $\mathcal{A}_K(c)$ ,  $c \in \mathbb{Z}$ , prime to  $2pf_K$ .

*Proof.* For all Galois character  $\psi$  of  $G_K$ , Lemma 9.1 leads to the identity:

$$\begin{aligned}\psi(\mathcal{A}_K(c)) &= \sum_{\sigma \in G_K} \Lambda_\sigma(c) \cdot \psi(\sigma) \\ &= (1 - \psi(c)) \cdot \prod_{\ell|f_K, \ell \nmid pf_\chi} (1 - \chi(\ell)\ell^{-1}) \cdot L_p(1, \chi) \\ &= (1 - \psi(c)) \cdot \prod_{\ell|f_K, \ell \nmid pf_\chi} (1 - \chi(\ell)\ell^{-1}) \cdot \chi(\Psi_{k_\chi})\end{aligned}$$

with  $\psi_1(\mathcal{A}_K(c)) = 0$  for the unit character  $\psi_1$ .

Since the matrix  $(\psi(\sigma))_{\psi, \sigma}$  is invertible with inverse  $\frac{1}{d}(\psi^{-1}(\sigma))_{\sigma, \psi}$ , this yields  $\Lambda_\sigma(c) = \frac{1}{d} \sum_{\psi} \psi^{-1}(\sigma) \psi(\mathcal{A}_K(c)) = \frac{1}{d} \sum_{\psi} \psi^{-1}(\sigma) (1 - \psi(c)) \cdot L_p(1, \psi)$ .

Whence the result using the expression of  $L_p(1, \psi)$  in Lemma 9.1.  $\square$

**9.4. Case of the real quartic field  $K$  of conductor 45161·37.** We recall from § 8.2 that  $m = 45161$  is totally ramified in  $K$ , that  $\ell = 37$  splits in the quadratic subfield  $k = \mathbb{Q}(\sqrt{m})$  and is ramified in  $K/k$ ; then  $p = 5$  totally splits in  $K$ . We have  $\mathcal{T}_k \simeq \mathbb{Z}/5^5\mathbb{Z}$ .

Denote the four characters by  $\psi_1, \psi_2, \psi_4$  &  $\psi_4^{-1}$  (orders 1, 2, 4, respectively) and let  $G_K = \{1, \sigma^2, \sigma, \sigma^{-1}\}$  with  $\sigma$  of order 4. We shall put  $\psi_4(\sigma) = i$ , and so on by conjugation and the relation  $\psi_2 = \psi_4^2$ .

Then, using the modified Solomon elements  $\Psi_k, \Psi_K$  (expressions (8.1), (8.2)):

$$\Psi_k = 5^5 \cdot u \quad \& \quad \Psi_K = \frac{v}{5} (\log(A) + \log(B) \sigma) (1 - \sigma^2),$$

where  $u$  and  $v$  are  $p$ -adic units,  $A$  &  $B = A^\sigma$  are the two independent units of  $K$  of relative norm 1.

We have to compute the coefficients  $\psi^{-1}(\sigma)(1 - \psi(c))$ , which gives the array:

	$\psi_1$	$\psi_2$	$\psi_4$	$\psi_4^{-1}$
1	0	1·2	1·(1-i)	1·(1+i)
$\sigma^2$	0	1·2	-1·(1-i)	-1·(1+i)
$\sigma$	0	-1·2	-i·(1-i)	i·(1+i)
$\sigma^{-1}$	0	-1·2	i·(1-i)	-i·(1+i)

Then the terms  $\prod_{\ell|f_K, \ell \nmid pf_\chi} (1 - \chi(\ell)\ell^{-1}) \cdot \chi(\Psi_{k_\chi})$  have the following values, depending on the character  $\psi$  in the summation of the theorem:

- $5^5 \cdot u$  for  $\psi_2$ , since  $1 - \chi_2(\ell)\ell^{-1} = 1 - 37^{-1} \sim 1$ ,
- $\frac{2v}{5} (\log(A) + i \log(B))$  &  $\frac{2v}{5} (\log(A) - i \log(B))$ , for  $\psi_4$  and  $\psi_4^{-1}$ .

We obtain, up to a  $p$ -adic unit, using the coefficients of the above array:

$$\begin{aligned}\mathcal{A}_K(c) &= \\ &= \left[ \frac{v}{5} [\log(A) + \log(B)] + 5^5 \cdot u \right] + \left[ \frac{v}{5} [-\log(A) - \log(B)] + 5^5 \cdot u \right] \cdot \sigma^2 + \\ &= \left[ \frac{v}{5} [-\log(A) + \log(B)] - 5^5 \cdot u \right] \cdot \sigma + \left[ \frac{v}{5} [\log(A) - \log(B)] - 5^5 \cdot u \right] \cdot \sigma^{-1} \\ &= 5^5 u \cdot (1 - \sigma)(1 + \sigma^2) \\ &\quad + v \left[ \frac{1}{5} [\log(A) + \log(B)] - \frac{1}{5} [\log(A) - \log(B)] \cdot \sigma \right] \cdot (1 - \sigma^2).\end{aligned}$$

We give  $A$ , one of the two units of relative norm 1 (the other being  $B = A^\sigma$ ):

```

377216797578975495402206020260112295002483855252847326395960961891321756
935656033880097414072613343385538964199960251752277854265043908282068622
071287/424760*x^3 -
863005972214749996449837366815586234260744443520807110375190268414267539
937539821074892103868728835668111842347981799323725052575447796376125480
7708541/7585*x^2 -
301058401703043815651487372068244675606729686675124486738439428208587682
003249385550605088262234049232685807258542997079887400411162925713036023
300228411/11480*x +
137753779960320144069066397981124894126287808388246384703621136571725449
454295610577594731673630502306081901547245942649393930683936045056394190
29007385081/410

```

So it is easy to compute  $A^4 - 1$ , congruent modulo  $5^8$  to:

$$5 \cdot \alpha = 317056 x^3 + 260605 x^2 + 260934 x + 182595,$$

whence  $\log(A) \sim 5 \cdot \alpha$ .

The decompositions into prime ideals of 5 (which is totally split in  $K/\mathbb{Q}$ ) and  $5 \cdot \alpha$  give respectively for the 5-places:

```

[[5, [-3, -2, 2, 2]~, 1, 1, [3, 4, 1, 1]~] 1]
[[5, [-3, 0, 2, -2]~, 1, 1, [2, 0, 4, 1]~] 1]
[[5, [-1, -2, -2, -2]~, 1, 1, [1, 1, 1, 1]~] 1]
[[5, [0, -1, -2, 2]~, 1, 1, [2, 2, 4, 1]~] 1]

[[5, [-3, -2, 2, 2]~, 1, 1, [3, 4, 1, 1]~] 2]
[[5, [-3, 0, 2, -2]~, 1, 1, [2, 0, 4, 1]~] 1]
[[5, [-1, -2, -2, -2]~, 1, 1, [1, 1, 1, 1]~] 2]
[[5, [0, -1, -2, 2]~, 1, 1, [2, 2, 4, 1]~] 1]

```

Dividing by 5, we find that  $\frac{1}{5}\log(A) \sim \pi_1 \cdot \pi_2$  then  $\frac{1}{5}\log(A^\sigma) \sim (\pi_1 \cdot \pi_2)^\sigma =: \pi_3 \cdot \pi_4$ , where the  $\pi_i$  are integers with valuation 1 at the four prime ideals dividing 5; thus the coefficient  $U - V\sigma = \frac{1}{5}\log(AB) - \frac{1}{5}\log(AB^{-1}) \sim u\pi_1 \cdot \pi_2 + u'\pi_3 \cdot \pi_4 - (u\pi_1 \cdot \pi_2 - u'\pi_3 \cdot \pi_4) \cdot \sigma$ , of  $1 - \sigma^2$  in  $\mathcal{A}_K(c)$  is such that  $U^2 + V^2 \equiv 2(u^2\pi_1^2 \cdot \pi_2^2 + u'^2\pi_3^2 \cdot \pi_4^2) \pmod{5}$  is 5-adically invertible. This gives the optimal annihilation of both  $\mathcal{T}_k$  (since  $\mathcal{T}_K = j_{K/k}(\mathcal{T}_k)$ ), and on the relative factor  $\mathcal{T}_K^* = 1$  as kernel of the relative norm  $1 + \sigma^2$  in  $K/k$  since the operation is given by the annihilator of  $\mathcal{T}_K^*$  which is  $2 \cdot (U - V\sigma) \sim (u\pi_1 \cdot \pi_2 + u'\pi_3 \cdot \pi_4) - (u\pi_1 \cdot \pi_2 - u'\pi_3 \cdot \pi_4) \cdot \sigma$ , defining the action of  $\sigma$ .

**9.5. The cyclic quartic field  $K$  of discriminant  $2^4 \cdot 1621^3 \cdot 677^2$ .** Let

$K = \mathbb{Q}(x)$  where  $x = \sqrt[4]{677 \frac{1621 + 39\sqrt{1621}}{2}}$ . This field is also defined by  $P = x^4 - 1097417x^2 + 18573782725$ . The conjugates of  $x$  are given by:

```
nfgaloisconj(P)=[-x, x, -1/132015*x^3+1571/195*x, 1/132015*x^3-1571/195*x]
```

We still consider the case  $p = 5$ . The prime  $\ell = 677$  splits in the quadratic subfield  $k = \mathbb{Q}(\sqrt{1621})$ , the ramified prime 2 does not split in  $k$ ; the class number of  $k$  is 1 and that of  $K$  is 4, so we obtain a trivial 5-class group and the following group structures giving, here, a non-trivial relative  $\mathcal{T}_K^*$ :

$$\mathcal{T}_k \simeq \mathbb{Z}/5^2\mathbb{Z}, \quad \mathcal{T}_K \simeq \mathbb{Z}/5^2\mathbb{Z} \times \mathbb{Z}/5^3\mathbb{Z}.$$

In  $k$ , the cyclotomic unit is the fundamental unit and is given by:

$$\varepsilon = \frac{119806883557}{26403} x^2 - \frac{3042847629386}{39};$$

we compute that  $\frac{1}{5} \cdot \log(\varepsilon) \sim 5^2 \sim \Psi_k$  as expected since  $\mathcal{T}_k = \mathcal{R}_k$ .

The cyclotomic units  $A$  and  $B = A^\sigma$  of  $K$ , of relative norm 1, are too large to be given here, but we can work with some representatives modulo a large power of 5. As in the previous example, we have to compute (up to 5-adic units since the Euler factors for 2 and 677 are invertible):

$$(9.1) \quad \left[ \frac{1}{5} [\log(A) + \log(B)] - \frac{1}{5} [\log(A) - \log(B)] \cdot \sigma \right] \cdot (1 - \sigma^2).$$

We see that  $\log(A)$  is of the form  $5 \cdot \alpha$ , where  $\alpha$  is a 5-adic unit, and that  $\frac{1}{5} [\log(A) - \log(B)]$  and  $\frac{1}{5} [\log(A) + \log(B)]$  are 5-adically invertible, so we consider for instance:

$$C := \frac{\log(A) + \log(B)}{\log(A) - \log(B)} \equiv 13 \cdot 5^2 x^3 + 5^3 x^2 + 19 \cdot 5^2 x + 57 \pmod{5^4}$$

and we verify that, despite the denominators 5,  $\frac{3}{5} \cdot x^3 - \frac{1}{5} \cdot x$  is an integer of  $K$  (congruent to  $x^\sigma$  modulo 5 as given by *nfgaloisconj*( $P$ )) so that:

$$C \equiv 5^3 \cdot 3 \cdot \left( \frac{3}{5} x^3 - \frac{1}{5} x + x^2 \right) + 57 \pmod{5^4}.$$

Since the exponent of  $\mathcal{T}_K$  is  $5^3$ , we obtain that the coefficient  $U - V \cdot \sigma$  (in (9.1)) is equal to  $(57 - \sigma) \cdot (1 - \sigma^2)$ ; thus the whole annihilator is:

$$\mathcal{A}_K(c) \equiv 5^2 \cdot u \cdot (1 - \sigma)(1 + \sigma^2) + v \cdot (57 - \sigma) \cdot (1 - \sigma^2) \pmod{5^4}.$$

So, on the factor  $\mathcal{T}_k$  the annihilator  $\mathcal{A}_K(c)$  acts as the order  $5^2$  of  $\mathcal{T}_k$ , and on the relative submodule  $\mathcal{T}_K^*$ , it acts as  $57 - \sigma$ , which is very satisfactory since 57 is of order 4 modulo  $5^3$  (note that  $57^2 + 1 = 5^3 \cdot 26$ ).

These examples show that  $\mathcal{A}_K(c)$  takes into account the whole structure of  $\mathcal{T}_K$ ; but when the Euler factor is not a  $p$ -adic unit because of a prime  $\ell \equiv 1 \pmod{p}$  which splits in  $k$  and is ramified in  $K/k$ , the annihilation is probably not optimal.

It should be useful to know if the annihilators, given more recently in the literature, have best properties or not in this point of view, which is not easy since numerical tests are absent (to our knowledge).

### 9.6. Ideal of annihilation for arbitrary real abelian number fields.

We do not make any assumption on  $p$  and  $G_K$ , nor on the decomposition of the primes  $\ell \mid f_K$  in the real abelian extension  $K/\mathbb{Q}$ .

If  $K/\mathbb{Q}$  is cyclic, one can choose  $c$  (prime to  $2pf_K$ ) such that for all  $\psi \neq 1$ ,  $1 - \psi(c)$  is non-zero with minimal  $p$ -adic valuation; this valuation is 0 as soon as  $d$  is not divisible by  $p$ , taking  $(\frac{K}{c})$  as a generator of  $G_K$ . Since in the non-cyclic case, this is impossible, we can consider the augmentation ideal  $\mathcal{I}_K = \langle 1 - (\frac{K}{c}), c \text{ prime to } 2pf_K \rangle_{\mathbb{Z}[G_K]}$  of  $G_K$  and the ideal:

$$\mathcal{I}_K \cdot \mathcal{A}_K$$

which annihilates  $\mathcal{T}_K$ . It is clear, from Corollary 7.3, that the pseudo-measure  $\mathcal{A}_K$  does not depend on  $\mathcal{I}_K$  and that any choice of  $\delta_K \in \mathcal{I}_K$  is such that  $\delta_K \mathcal{A}_K \in \mathbb{Z}_p[G_K]$ .

In a  $p$ -group  $G_K$  of  $p$ -rank  $r$ ,  $\delta_K = \sum_{i=1}^r \lambda_i \cdot (1 - \sigma_i)$ , where the generators  $\sigma_i$  are suitable Artin symbols of integers  $c_i$  prime to  $2pf_K$ ; then the characters  $\psi$  may be written  $\psi = \prod_{i=1}^r \psi_i$ , with obvious definition of the  $\psi_i$ , so that  $\psi(\delta_K) = \sum_{i=1}^r \psi(\lambda_i) \cdot (1 - \psi_i(\sigma_i)) = \sum_{i=1}^r \psi(\lambda_i) \cdot (1 - \xi_i)$ , where the  $\xi_i$  are roots of unity of  $p$ -power order. So we can minimize the  $p$ -adic valuations of the  $\psi(\delta_K)$  to obtain the best annihilator.

For instance, if  $K$  is the compositum of two cyclic cubic fields and  $p = 3$ , whatever the choice of  $\delta_K = \lambda_1(1 - \sigma_1) + \lambda_2(1 - \sigma_2)$ ,  $\lambda_1, \lambda_2$  prime to 3, where  $\sigma_1, \sigma_2$  are two generators of  $G_K$ , then  $\psi(\delta_K) \sim 1 - j$  for 6 characters and  $\psi(\delta_K) \sim 3$  for 2 other characters  $\psi \neq 1$ . So the result depends on the structures of the  $\mathcal{T}_k$  of the 4 cubic subfields  $k$  of  $K$ .

*Remarks 9.5.* (i) Let  $k$  be a subfield of  $K$  and let  $j_{K/k}$  be the “transfer map”  $\mathcal{T}_k \rightarrow \mathcal{T}_K$ . Then, for  $\delta_K \mathcal{A}_K$ , we get:

$$(j_{K/k}(\mathcal{T}_k))^{\delta_K \mathcal{A}_K} = j_{K/k}(\mathcal{T}_k^{\text{N}_{K/k}(\delta_K \mathcal{A}_K)}) \simeq \mathcal{T}_k^{\text{N}_{K/k}(\delta_K \mathcal{A}_K)} = \mathcal{T}_k^{\mathcal{E}_k \cdot \delta_k \mathcal{A}_k};$$

indeed, this comes from the injectivity of the transfer since the Leopoldt conjecture is true in abelian extensions (see e.g., [8, Theorem IV.2.1]); then if the product of Euler factors  $\mathcal{E}_k := \prod_{\ell|f_K, \ell \nmid pf_k} \left(1 - \frac{1}{\ell} \left(\frac{k}{\ell}\right)\right)$  is invertible (i.e.,  $\chi(\mathcal{E}_k)$  prime to  $p$  for all  $\chi$ ), this means that there is no loss of information by using the annihilation of  $\mathcal{T}_K$  by the  $\delta_K \mathcal{A}_K$ , instead of that of  $\mathcal{T}_k$  by the  $\delta_k \mathcal{A}_k$ ; otherwise, it is not possible to eliminate the Euler factors “hidden” in  $\delta_K \mathcal{A}_K$  when they are non-invertible (although they are never zero) unless to restrict ourselves to the use of the  $\delta_k \mathcal{A}_k$  for  $\mathcal{T}_k$ , at the cost of a weaker information on the Galois structure.

(ii) The  $G_K$ -module  $\mathcal{T}_K$  gives rise to the following submodules or quotients-modules which have interesting arithmetical meaning and are of course annihilated by the  $\delta_K \mathcal{A}_K$ :<sup>3</sup>

- The submodule  $\mathcal{C}_K^\infty := \text{Gal}(K_\infty H_K / K_\infty)$  isomorphic to a sub-module of  $\mathcal{C}_K$ . Note that if  $p$  is unramified in  $K/\mathbb{Q}$  and if (for  $p = 2$ )  $-1$  is not a local norm at 2, then  $\mathcal{C}_K^\infty \simeq \mathcal{C}_K$  (cf. (2.1)), which explains that, in general, one says that the  $p$ -class group is annihilated by the annihilators of  $\mathcal{T}_K$ .

- The module  $\mathcal{W}_K$  and the normalized  $p$ -adic regulator  $\mathcal{R}_K$  defining the exact sequence (2.2).

- The Bertrandias–Payan module  $\mathcal{BP}_K := \mathcal{T}_K / \mathcal{W}_K$  for which the fixed field  $H_K^{\text{bp}}$  by  $\mathcal{W}_K$  in  $H_K^{\text{pr}} / K_\infty$  is the compositum of the  $p$ -cyclic extensions of  $K$  which are embeddable in  $p$ -cyclic extensions of arbitrary large degree.

Then some “logarithmic objects” defined and studied by Jaulent (see [15], [16, § 2.3, Schéma] and [3]), in a theoretical and computational point of view:

- The logarithmic class group  $\tilde{\mathcal{C}}_K := \text{Gal}(H_K^{\text{lc}} / K_\infty)$  ( $H_K^{\text{lc}}$  is the maximal abelian locally cyclotomic pro- $p$ -extension of  $K$ ), defining the exact sequence  $1 \rightarrow \tilde{\mathcal{C}}_K^{[p]} \rightarrow \tilde{\mathcal{C}}_K \rightarrow \mathcal{C}_K^{S_\infty} \rightarrow 1$  ( $\mathcal{C}_K^S := \mathcal{C}_K / \mathcal{C}_K(S)$  is the  $p$ -group of  $S$ -classes of  $K$  and  $\tilde{\mathcal{C}}_K^{[p]}$  the subgroup generated by  $S$ ).

- The “logarithmic regulator”  $\tilde{\mathcal{R}}_K$  as quotient of the group of “semi-local logarithmic units” by the “global logarithmic units”.

<sup>3</sup>For some  $\mathcal{C}_K := \text{Gal}(H_K^*/K)$ ,  $H_K^* \subseteq H_K^{\text{pr}}$ , we put  $\mathcal{C}_K^\infty := \text{Gal}(K_\infty H_K^* / K_\infty)$ .

## 10. CONCLUSION

This elementary study, especially with the help of numerical computations, shows that the broad generalizations of  $\mathbb{Z}_p[G_K]$ -annihilations, that come from values of partial  $\zeta$ -functions, with various base fields (see, e.g., [18, 19, 20, 24] among many others), may be difficult to analyse, owing to the fact that the results are not so efficient (especially in the non semi-simple and/or the non-cyclic cases), and that some degeneracies may occur because of Euler factors as soon as the  $p$ -adic pseudo-measures that are used are of “Stickelberger’s type” like Solomon’s elements or cyclotomic units.

Moreover, depending on whether one deals with imaginary or real fields, the suitable object to be annihilated is not defined in an unique way as shown by the context of the present paper about the  $G_K$ -module  $\mathcal{T}_K$ . Moreover, roughly speaking, some objects are relative to the  $L_p(0, \chi)$  (e.g., relative classes), while some other are relative to  $L_p(1, \chi)$  (e.g., groups  $\mathcal{T}_K$ ), and it is well known that the points “ $s = 0$ ” and “ $s = 1$ ” are mysteriously independent, giving sometimes abundant “Siegel zeros” near 1, as explained by Washington in many papers (see [11] and its bibliography), whence an unpredictable order of magnitude of the annihilators.

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