

**Zeitschrift:** Commentarii Mathematici Helvetici  
**Herausgeber:** Schweizerische Mathematische Gesellschaft  
**Band:** 63 (1988)  
  
**Artikel:** Maximal hermitian forms over ...G .  
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**DOI:** <https://doi.org/10.5169/seals-48204>

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# Maximal hermitian forms over $\mathbb{Z}G$

JORGE F. MORALES

## 0. Introduction

Let  $G$  be a finite group and let  $V$  denote a representation of  $G$  over the field of rational numbers. It is a standard fact that  $V$  admits a symmetric nondegenerate bilinear form  $B: V \times V \rightarrow \mathbb{Q}$  invariant under  $G$ . Let  $B$  be such a form on  $V$  and let  $L$  be a full  $\mathbb{Z}G$ -lattice in  $V$ . We denote by  $L_B^*$  the dual lattice of  $L$  with respect to  $B$ , that is

$$L_B^* = \{x \in V : B(x, L) \subset \mathbb{Z}\}$$

A full  $\mathbb{Z}G$ -lattice  $L$  is said to be *integral* with respect to  $B$  if the form  $B$  takes integral values on  $L$ , or equivalently, if  $L$  is contained in  $L_B^*$ . We define the *minimal discriminant* of  $(V, B)$  to be the positive integer

$$d_B(V) = \min_L [L_B^* : L]$$

where  $L$  runs over all full  $\mathbb{Z}G$ -lattices of  $V$  integral with respect to  $B$ .

We define the *absolute minimal discriminant* of  $V$  to be the integer

$$d(V) = \min_B d_B(V)$$

where  $B$  runs over all symmetric nondegenerate  $G$ -invariant bilinear forms on  $V$ . Clearly  $d(V)$  depends only on the representation  $V$  and is a measure of the extent to which  $V$  fails to admit a self-dual  $\mathbb{Z}G$ -lattice. If  $V$  is a permutation representation, obviously  $d(V) = 1$ . If  $V$  is an absolutely simple representation of  $G$ , it follows from a theorem of W. Feit (see [F] Thm. 3.2) that the prime divisors of  $d(V)$  divide  $|G|$ .

In Section 1 we show that for a given form  $B$ , the set of lattices of  $V$  realizing the minimal discriminant  $d_B(V)$  has a natural structure of a connected graph. In the case where  $V$  is absolutely simple, this graph is finite.

In Section 2 we consider the case where  $G$  is a  $p$ -group and  $V$  is a simple representation of  $G$  over  $\mathbb{Q}$ . We show that in this case the absolute minimal discriminant  $d(V)$  is equal to  $p$ . We give a lower bound for the number of distinct (i.e. non equivariantly isometric) lattices realizing the minimal discriminant in terms of class numbers of cyclotomic fields. Under slightly more restrictive hypothesis, we show that the lattices with minimal discriminant are (non canonically) in 1–1 correspondance with an ideal class group. We show that all the maximal lattices in  $V$  belong to the same genus if and only if the cohomological condition  $H^1(G, L) \cong \mathbb{F}_p$  is verified by some maximal lattice  $L$ . Finally, to illustrate this result, we define  $G$  to be the semidirect product of  $C_p$  by  $C_p \times C_p$  and  $V$  to be the unique simple nonabelian representation of this group over  $\mathbb{Q}$ . In this example  $V$  contains only one genus of maximal lattices for  $p = 3$  and at least  $(p + 1)$  genera for  $p \geq 5$ .

## 1. The graph of lattices with minimal discriminant

In this section  $G$  will denote a finite group,  $V$  a representation of  $G$  over  $\mathbb{Q}$  and  $B : V \times V \rightarrow \mathbb{Q}$  a symmetric nondegenerate  $G$ -form on  $V$ .

**DEFINITION.** A full  $\mathbb{Z}G$ -lattice  $L$  in  $V$ , integral with respect to  $B$ , is maximal if it is not properly contained in any full  $\mathbb{Z}G$ -lattice integral with respect to  $B$ .

(1.1) **LEMMA.** *The following properties are equivalent*

- a)  $[L_B^* : L] = d_B(V)$
- b)  $L$  is maximal
- c) *The associated torsion form  $(L_B^*/L, B)$  is anisotropic (i.e. does not admit any non zero totally isotropic subgroup preserved by  $G$ ).*

*Proof.* Clearly  $a) \Rightarrow b) \Rightarrow c)$ . To see that  $c) \Rightarrow a)$  we recall that the weak Witt class of  $(L_B^*/L, B)$  as a torsion  $G$ -form is independent of the choice of  $L$  and has a unique anisotropic representative (see for instance [Sch] Chapter 5 and Chapter 7 Section 5). Let  $M$  be an integral  $\mathbb{Z}G$ -lattice with  $[M_B^* : M] = d_B(V)$ . The torsion form  $(M_B^*/M, B)$  is also anisotropic and lies in the same weak Witt class as  $(L_B^*/L, B)$ . By uniqueness of the anisotropic representative, they are actually isometric. In particular, the underlying finite  $\mathbb{Z}G$ -modules both have the same order.  $\square$

(1.2) LEMMA. *Let  $L$  be a maximal integral  $\mathbb{Z}G$ -lattice. Then  $L_B^*/L$  is a semi-simple  $\mathbb{Z}G$ -module.*

*Proof.* Let  $X \subset L_B^*/L$  be the intersection of all maximal sub  $\mathbb{Z}G$ -modules of  $L_B^*/L$  (i.e. the radical of  $L_B^*/L$ ). Let  $X^\perp$  be the orthogonal complement of  $X$ . Since  $L_B^*/L$  is anisotropic, we have  $X \cap X^\perp = \{0\}$  and therefore  $X + X^\perp = L_B^*/L$ . By Nakayama's lemma we have  $X^\perp = L_B^*/L$  and therefore  $X = \{0\}$ .  $\square$

(1.3) PROPOSITION. *Let  $L_1$  and  $L_2$  be maximal integral  $\mathbb{Z}G$ -lattices in  $(V, B)$ . Then we have*

$$\ell(L_1/L_1 \cap L_2) = \ell(L_2/L_1 \cap L_2)$$

where  $\ell(X)$  is the length of  $X$  as a  $\mathbb{Z}G$ -module, that is the length of a composition series for  $X$  (see [C-R] §3).

*Proof.* Let  $L_1 \cap L_2 = S_0 \subsetneq S_1 \subsetneq \cdots \subsetneq S_n = L_1$  be a composition series. Dualizing this series using the form  $B$  we obtain

$$L_1^* + L_2^* = S_0^* \supsetneq S_1^* \supsetneq \cdots \supsetneq S_n^* = L_1^*$$

and intersecting with  $L_2$  we obtain

$$L_2 = S_0^* \cap L_2 \supset S_1^* \cap L_2 \supset \cdots \supset S_n^* \cap L_2 = L_1^* \cap L_2$$

By the maximality of  $L_1$  we have  $L_1^* \cap L_2 = L_1 \cap L_2$ . On the other hand, the quotient  $(S_i^* \cap L_2)/(S_{i+1}^* \cap L_2)$  is naturally embedded in the simple module  $S_i^*/S_{i+1}^*$ . Thus  $(S_i^* \cap L_2)/(S_{i+1}^* \cap L_2)$  is either 0 or a simple module. Hence,

$$n = \ell(L_1/L_1 \cap L_2) \geq \ell(L_2/L_1 \cap L_2).$$

By symmetry we conclude

$$\ell(L_1/L_1 \cap L_2) = \ell(L_2/L_1 \cap L_2) \quad \square$$

DEFINITION. Let  $L_1$  and  $L_2$  be maximal  $\mathbb{Z}G$ -lattices in  $(V, B)$ . We define the distance between  $L_1$  and  $L_2$  by

$$\delta(L_1, L_2) := \ell(L_1/L_1 \cap L_2).$$



Observe that  $\delta$  is a symmetric function by Proposition 1.3. The lattices  $L_1$  and  $L_2$  are said to be adjacent (or neighbors) if  $\delta(L_1, L_2) = 1$ . The notion of neighbors (benachbarte Formen) was introduced by M. Kneser (see [K]) for quadratic forms without a group action, and has proved to be a powerful tool for explicit constructions.

The set  $\Gamma_B(V)$  of all integral maximal  $\mathbb{Z}G$ -lattices in  $V$  has a natural graph structure. The vertices are the elements of  $\Gamma_B(V)$  and two vertices are joined by an edge if they represent adjacent lattices in the sense previously defined.

(1.4) THEOREM. *The graph  $\Gamma_B(V)$  is connected.*

*Proof.* Let  $L_1$  and  $L_2$  be two distinct maximal lattices. By induction, it is enough to show there exists a maximal lattice  $L$  such that

$$\delta(L, L_1) = 1 \quad \text{and} \quad \delta(L, L_2) < \delta(L_1, L_2)$$

The lattices  $L_1$  and  $L_2$  being distinct, the intersection  $L_1 \cap L_2$  is contained in a proper sublattice  $M$  of  $L_1$ , where  $L_1/M$  is a simple  $\mathbb{Z}G$ -module.

We define

$$L := M^* \cap L_2 + M$$

where  $M^* = M_B^*$ . Clearly  $L$  is integral. Let us now compute the index  $[L : M^* \cap L_2]$ . We have

$$[L : M^* \cap L_2] = [M : M \cap M^* \cap L_2] = [M : M \cap L_2]$$

On the other hand

$$[L_2 : M^* \cap L_2] = [M + L_2^* : L_2^*] = [M : L_2^* \cap M] = [M : L_2 \cap M]$$

(the last equality uses  $L_2 \cap M = L_2^* \cap M$  which is a consequence of the maximality of  $L_2$ ).

Thus we have  $[L : M^* \cap L_2] = [L_2 : M^* \cap L_2]$ . Consequently  $[L^* : L] = [L_2^* : L_2] = d_B(V)$ . According to Lemma 1.1 the lattice  $L$  is maximal.

Now

$$L \cap L_1 = M^* \cap L_2 \cap L_1 + M = L_2 \cap L_1 + M = M$$

thus

$$\delta(L, L_1) = \ell(L_1/L_1 \cap L) = \ell(L_1/M) = 1.$$

It is left to show that  $\delta(L, L_2) < \delta(L_1, L_2)$ . We have

$$L \cap L_2 = (M^* \cap L_2 + M) \cap L_2 = M^* \cap L_2$$

Hence

$$\begin{aligned} \delta(L, L_2) &= \ell(L_2/L \cap L_2) = \ell(L_2/M^* \cap L_2) \stackrel{(1)}{=} \ell((M + L_2^*)/L_2) \\ &= \ell(M/L_2^* \cap M) \stackrel{(2)}{=} \ell(M/L_2 \cap M) \end{aligned}$$

where (1) uses the fact that a finite module and its character module have the same length and (2) uses the maximality of  $L_2$ .

On the other hand we have

$$L_1 \cap L_2 \subset M \cap L_2 \subset M \subsetneq L_1.$$

Hence,

$$\delta(L_1, L_2) = \ell(L_1/L_1 \cap L_2) > \ell(M/M \cap L_2) = \delta(L, L_2) \quad \square$$

(1.5) THEOREM. *If  $V$  is an absolutely simple representation of  $G$ , then the graph  $\Gamma_B(V)$  is finite and connected.*

*Proof.* Recall that absolutely simple means  $\text{End}_G(V) = \mathbb{Q}$ . The lattices in  $\Gamma_B(V)$  all have the same discriminant. It follows from this fact and Theorem 1.1 in [M] that  $\Gamma_B(V)$  has finitely many orbits under the action of the automorphism group of the  $G$ -form  $(V, B)$ . It remains to show that each orbit is finite. In fact each orbit consists of precisely one lattice: since  $\text{End}_G(V) = \mathbb{Q}$ , the only  $G$ -endomorphisms of  $V$  which additionally preserve the form  $B$  are 1 and  $-1$ , and clearly they preserve any lattice.  $\square$

## 2. The case where $G$ is a $p$ -group

In this section  $G$  will be a  $p$ -group, where  $p$  is an *odd* prime number, and  $V$  will be a *faithful* simple  $\mathbb{Q}G$ -module. The endomorphism field  $\text{End}_G(V)$  will be denoted by  $E$ .

(2.1) LEMMA. *The endomorphism field  $E$  is equal to a cyclotomic field  $\mathbb{Q}(\zeta)$ , where  $\zeta$  is a primitive  $p^m$ -th root of 1.*

*Proof.* From representation theory (see for instance [H] 14.7b) we know that the center  $Z(E)$  of  $E$  is equal to the field  $\mathbb{Q}(\chi)$ , where  $\chi$  is an absolutely irreducible factor of the character of  $V$ . Indeed  $\mathbb{Q}(\chi)$  is contained in the cyclotomic field  $\mathbb{Q}(\zeta_{p^a})$ , where  $p^a$  is the exponent of  $G$ . Since  $E = Z(E)$  by Schilling's Theorem (see [R] Theorem 41.9),  $E$  is contained in  $\mathbb{Q}(\zeta_{p^a})$ .

On the other hand, since  $G$  is a  $p$ -group, its center  $Z(G)$  is nontrivial and since  $V$  is faithful, it maps non trivially into the multiplicative group of  $E$ , generating a cyclotomic subfield  $\mathbb{Q}(\zeta_{p^b})$  of  $E$ , where  $p^b$  is the exponent of  $Z(G)$ . The relative Galois group  $\text{Gal}(\mathbb{Q}(\zeta_{p^a})/\mathbb{Q}(\zeta_{p^b}))$  is cyclic of order  $p^{a-b}$ . Thus all the intermediate subfields between  $\mathbb{Q}(\zeta_{p^a})$  and  $\mathbb{Q}(\zeta_{p^b})$  are cyclotomic. So is, in particular, the field  $E$ .  $\square$

The  $\mathbb{Q}G$ -module  $V$  can be regarded as a vector space over its endomorphism ring  $E$ . Furthermore,  $V$  can be regarded as an absolutely simple  $EG$ -module.

(2.2) LEMMA. *Let  $L \subset V$  be a full  $\mathbb{Z}G$ -lattice and let  $O_E$  be the maximal order of  $E$ . Then for every prime  $q \neq p$  we have*

$$\text{End}_G(L)_q = (O_E)_q$$

*Proof.* For  $q \neq p$ , the ring  $\mathbb{Z}_q G$  is a maximal order (see [R] Theorem 41.1). Hence  $\text{End}_G(L_q)$  is a maximal order as well (see [R] Chap. 21, Exercise 1). Therefore, using the canonical identification  $\text{End}_G(L_q) = \text{End}_G(L)_q$ , we get the equality  $(O_E)_q = \text{End}_G(L)_q$ .  $\square$

Let  $B: V \times V \rightarrow \mathbb{Q}$  be a  $G$ -invariant symmetric form. It is easy to see that the adjoint involution on  $E = \text{End}_G(V)$  is actually complex conjugation. Let  $h: V \times V \rightarrow E$  be the unique hermitian form on  $V$  such that the following triangle commutes

$$\begin{array}{ccc} V & \xrightarrow{ad(B)} & \text{Hom}_{\mathbb{Q}}(V, \mathbb{Q}) \\ & \searrow^{ad(h)} & \nearrow_{Tr_{E/\mathbb{Q}}} \\ & \text{Hom}_E(V, E) & \end{array}$$

Clearly  $h$  is also  $G$ -invariant. Now let  $L$  be a full  $\mathbb{Z}G$ -lattice in  $V$  on which  $B$  takes integral values. Suppose in addition that  $\text{End}_G(L)$  is equal to the maximal order  $O_E$ . Then the hermitian form  $h$  restricted to  $L$  takes values in the co-different  $D_{E/\mathbb{Q}}^{-1}$  of  $E/\mathbb{Q}$ . It is well known that  $D_{E/\mathbb{Q}}$  is an odd power of the prime ideal  $\mathfrak{p}$  lying above  $p$ . The prime ideal  $\mathfrak{p}$  is generated by  $\alpha = \zeta - \zeta^{-1}$  and therefore  $D_{E/\mathbb{Q}} = (\alpha^v)$ , where  $v$  is an odd power. Let  $f$  denote the scaled form  $\alpha^v h$ , which is indeed skew-hermitian and takes integral values on  $L$ .

(2.3) LEMMA. *Let  $L$  be a full  $O_E G$ -lattice in  $V$ . Then we have*

- a)  $L_f^* = L_B^*$
- b)  $L$  is integral maximal with respect to  $B$  if and only if it is integral maximal with respect to  $f$

*Proof.* The proof of Lemma 2.3 is straightforward from the definition of  $f$ .  $\square$

(2.4) PROPOSITION. *Let  $L \subset V$  be a  $\mathbb{Z}G$ -lattice maximal with respect to  $B$ . Then  $\text{ord}_p [L_B^* : L] = 1$ .*

*Proof.* Since, by Lemma 1.1, all maximal lattices  $L$  have the same index  $[L_B^* : L]$ , it will be enough, using Lemma 2.3, to prove Proposition 2.4 for a  $O_E G$ -lattice  $L$  in  $V$  maximal with respect to  $f$ .

Since  $V$  is absolutely simple as an  $EG$ -module, its dimension over  $E$  divides  $|G|$  (see for instance [H] Theorem 12.6). It is in particular an odd number (we assumed  $p$  odd), consequently

$$\overline{\det(f)} = \det(f^*) = \det(-f) = -\det(f).$$

It is easy to see that an element  $x \in E$  with the property  $\bar{x} = -x$  has necessarily odd order at the prime ideal  $\mathfrak{p}$  of  $E$  which lies above  $p$ . This applies in particular to  $\det(f)$ .

Hence

$$\text{ord}_p [L^* : L] = \text{ord}_p (N_{E/\mathbb{Q}}(\det(f))) = \text{ord}_p (\det(f)) \equiv 1(2)$$

(where  $L^*$  is the simplified notation for  $L_B^*$  or  $L_f^*$ ).

On the other hand,  $L$  being maximal, the torsion  $G$ -form  $(L_p^*/L_p, B)$  is anisotropic and the underlying  $\mathbb{Z}G$ -module is semi-simple (see Lemma 1.2). Since  $G$  is a  $p$ -group, it acts trivially on semi-simple  $\mathbb{Z}_p G$ -modules (see [C-R] Theorem 5.24). Therefore  $(L_p^*/L_p, B)$  is nothing but an anisotropic quadratic space over  $\mathbb{F}_p$ . Therefore  $\text{ord}_p [L_p^* : L_p] = \dim_{\mathbb{F}_p} (L_p^*/L_p) \leq 2$ . But we already know that  $\text{ord}_p [L_p^* : L_p]$  is odd. Thus  $\text{ord}_p [L_p^* : L_p] = 1$ .  $\square$

(2.5) COROLLARY. *The discriminant of a full  $\mathbb{Z}G$ -lattice in  $V$ , integral with respect to  $B$ , is divisible by  $p$ .*

Our next goal is to prove the existence of  $G$ -forms on  $V$  which admit a full

$\mathbb{Z}G$ -lattice with discriminant exactly equal to  $p$ . This will prove that the number  $d(V)$  defined in Section 1 is equal to  $p$ .

The main ingredient in the existence theorem is the following result of Galois cohomology that was kindly communicated to me by P. Conner.

(2.6) PROPOSITION. *Let  $S$  be the set containing all the infinite primes of  $E$  and the unique finite ramified prime  $\mathfrak{p}$ . Let  $\alpha$  be an  $S$ -ideal preserved by the involution on  $E$ . Then there exists  $\lambda \in F := \{x \in E : \bar{x} = x\}$  totally positive and an  $S$ -ideal  $\mathfrak{b}$  such that  $\alpha = \lambda N_{E/F}(\mathfrak{b})$ .*

*Proof.* It is enough to prove the proposition for an inert prime ideal  $\alpha$ , the decomposed case being trivial.

Let  $\pi = N_{E/F}(\Pi)$ , where  $\Pi$  is a generator of  $\mathfrak{p}$ . The prime element  $\pi$ , being a norm, is totally positive. There is an element  $\lambda \in F'$  such that the Hilbert symbol  $(\lambda, \pi)_q = -1$  for  $q = \alpha$  or  $q = (\pi)$  and  $(\lambda, \pi)_q = 1$  otherwise (see for instance [O] Theorem 71.19). We claim that  $\lambda$  has the required properties. By definition  $\lambda$  is a norm locally at all primes except  $\alpha$  and  $(\pi)$ . It is in particular totally positive. The prime  $\alpha$  being inert, we have the isomorphism (see [S] Chap. V, Prop. 3)

$$\text{ord}_\alpha : \hat{H}^0(\text{Gal}(E_\alpha/F_\alpha), E_\alpha^\times) \rightarrow \mathbb{Z}/2\mathbb{Z}.$$

By construction,  $\lambda$  is not a norm in  $E_\alpha$ , therefore  $\text{ord}_\alpha(\lambda) \equiv 1(2)$ . Hence  $\lambda^{-1}\alpha$  is locally a norm at all  $S$ -primes, i.e.  $\lambda^{-1}\alpha = N_{E/F}(\mathfrak{b})$  for some  $S$ -ideal  $\mathfrak{b}$ .  $\square$

(2.7) THEOREM. *Let  $R$  denote the ring  $\mathbb{Z}[p^{-1}]$ . There exists a symmetric  $G$ -form  $B : V \times V \rightarrow \mathbb{Q}$  which admits a unimodular  $RG$ -lattice  $M$ . Furthermore,  $B$  can be chosen to be positive definite and is the only (up to equivariant isometry) positive definite  $G$ -form on  $V$  admitting a unimodular  $RG$ -lattice.*

*Proof.* Let  $S$  be the set of all ramified primes of  $E$ . The ring  $O_S$  of  $S$ -integers of  $E$  is precisely the integral closure of  $R$  in  $E$ . The  $RG$ -lattices in  $V$  can be, by lemma 2.2, regarded as  $O_S G$ -lattices.

We observe first that any two  $RG$ -lattices  $M$  and  $N$  are ideal-equivalent, that is, there exists an  $S$ -ideal  $\alpha$  of  $E$  such that  $\alpha M = N$ . Notice that if such an ideal exists, it is uniquely determined by  $\alpha = \text{Hom}_{RG}(M, N)$ . Let us define  $\alpha = \text{Hom}_{RG}(M, N)$  and show  $\alpha M = N$ .

Since the order  $RG$  is maximal (see [C] Theorem 41.1),  $M$  is projective as an  $RG$ -module, that is the functor  $\text{Hom}_{RG}(M, -)$  is exact. By applying it to the exact sequence

$$0 \rightarrow \alpha M \rightarrow N \rightarrow N/\alpha M \rightarrow 0$$

we obtain

$$0 \rightarrow \alpha \rightarrow \alpha \rightarrow \text{Hom}_{RG}(M, N/\alpha M) \rightarrow 0$$

where the map  $\alpha \rightarrow \alpha$  is the identity. Therefore  $\text{Hom}_{RG}(M, N/\alpha M) = 0$ . The projectivity of  $M$  implies immediately  $N/\alpha M = 0$ .

Let  $C: V \times V \rightarrow \mathbb{Q}$  be a positive definite  $G$ -form on  $V$  and  $N$  any  $RG$ -lattice in  $V$ . Let  $\alpha$  be the  $S$ -ideal  $\text{Hom}_{RG}(N, N_C^*)$ . The ideal  $\alpha$  is by construction preserved by the involution in  $E$ . By Proposition 2.6 there exists  $\lambda \in F^*$  totally positive and an  $S$ -ideal  $\mathfrak{b}$  such that  $\alpha = \lambda \mathfrak{b} \bar{\mathfrak{b}}$ .

Let  $M = \mathfrak{b}N$  and  $B(x, y) = C(\lambda x, y)$ . We have

$$M_B^* = \lambda^{-1} M_C^* = \lambda^{-1} (\bar{\mathfrak{b}})^{-1} N_C^* = \lambda^{-1} (\bar{\mathfrak{b}})^{-1} \alpha N = \mathfrak{b} N = M$$

Thus  $M$  is unimodular with respect to  $B$ . Since  $\lambda$  has been chosen totally positive and  $C$  positive definite, the form  $B(x, y) = C(\lambda x, y)$  is positive definite as well.

Let us now prove the uniqueness of  $B$ . Let  $B'$  be another positive definite  $G$ -form on  $V$  which also admits a unimodular  $RG$ -lattice. Since  $V$  is a simple representation there exists  $\mu \in F^*$  such that  $B'(x, y) = B(\mu x, y)$ . Clearly  $\mu$  is totally positive and therefore it is a norm at all infinite primes. Let  $h: V \times V \rightarrow E$  be the hermitian form canonically associated to  $B$ . The scaled form  $\mu h$  is indeed the hermitian form corresponding to  $B'$ . Since  $h$  and  $\mu h$  both admit unimodular  $O_S G$ -lattices,  $\det(h)$  and  $\det(\mu h) = \mu^{[V:E]} \det(h)$  are both  $S$ -units modulo the norms. Since  $[V:E]$  is odd, this implies that  $\mu$  is a  $S$ -unit modulo the norms. We can therefore assume that  $\mu$  is a  $S$ -unit.

We want now to show that  $\mu$  is a norm everywhere locally. If  $\mathfrak{q}$  is an inert prime of  $F$ , the units of  $F_{\mathfrak{q}}$  are all norms from  $E_{\mathfrak{q}}$  (see [S] Proposition 3 and Corollary), thus  $\mu$  is a norm at  $\mathfrak{q}$ . If  $\mathfrak{q}$  is a decomposed prime, everything is a norm from  $E_{\mathfrak{q}}$ . Thus  $\mu$  is a norm at all unramified primes and at the infinite primes. By Hilbert's Reciprocity Theorem,  $\mu$  is also a norm at the unique ramified finite prime. We conclude by Hasse's Norm Theorem that  $\mu$  is a global norm, that is, there exists  $\alpha \in E^*$  such that  $\mu = \alpha \bar{\alpha}$ . Indeed  $B'(x, y) = B(\mu x, y) = B(\alpha x, \alpha y)$ .  $\square$

**DEFINITION.** Let  $C: V \times V \rightarrow \mathbb{Q}$  be a  $G$ -form and  $B: V \times V \rightarrow \mathbb{Q}$  a positive definite  $G$ -form. We know that  $C(x, y) = B(\lambda x, y)$  for some  $\lambda \in F^*$ . We define the  $G$ -signature  $s_G(C)$  of  $C$  as the signature of  $\lambda$  (that is, the collection of signs for the various embeddings of  $F$  in  $\mathbb{R}$ ). Clearly this definition is independent of the choice of  $B$ .

(2.8) THEOREM. *For a given signature  $s = (s_v)$  there exists a unique (up to equivariant isometry)  $G$ -form  $C$  with  $s_G(C) = s$  which admits an integral  $\mathbb{Z}G$ -lattice of discriminant equal to  $p$ .*

*Proof.* Note that the element  $\lambda \in F$  of Proposition 2.6 can be chosen with any prescribed signature. It follows from this observation and from the proof of Theorem 2.7 that there exists a unique (up to equivariant isometry)  $G$ -form  $C$  on  $V$  with  $s_G(C) = s$  which in addition admits a unimodular  $RG$ -lattice  $M$ . To construct a  $\mathbb{Z}G$ -lattice  $L$  of discriminant  $p$  from  $M$ , we take a maximal  $\mathbb{Z}_p G$ -lattice  $N \subset V_p$  and define  $L =: N \cap M$ . The lattice  $L$  constructed in this way will have discriminant  $p$  in virtue of Proposition 2.4.  $\square$

Our next goal is to describe (up to equivariant isometry) the  $\mathbb{Z}G$ -lattices in  $V$  integral with discriminant  $p$  for a given form  $B$  on  $V$ .

Let  $I^1(E)$  denote the group of ideals  $\alpha$  of  $E$  satisfying  $\alpha\bar{\alpha} = O_E$ . Notice that such an ideal does not contain any ramification. Let  $P^1(E)$  denote the group of principal ideals  $(a)$  with  $a\bar{a} = 1$ .

(2.9) THEOREM. *Let  $B: V \times V \rightarrow \mathbb{Q}$  be a  $G$ -form on  $V$  which admits a  $\mathbb{Z}G$ -lattice  $L \subset V$  with discriminant  $p$ . Then*

- a) *The group  $I^1(E)/P^1(E)$  acts freely on the set of isomorphism classes of lattices in the genus of  $L$ .*
- b) *If in addition  $\text{End}_{\mathbb{Z}G}(L) = O_E$  then the action of  $I^1(E)/P^1(E)$  on the set of isomorphism classes of lattices in the genus of  $L$  is transitive.*

*Proof.* a) Let  $L \subset V$  be a maximal integral  $\mathbb{Z}G$ -lattice in  $V$ . As in the proof of Theorem 2.7, we denote by  $O_S$  the ring of  $S$ -integers of  $E$ , where  $S$  is the finite set of ramified primes. We denote by  $L_S$  the tensor product  $L \otimes \mathbb{Z}[p^{-1}]$ , which is, by Lemma 2.2, an  $O_S G$ -lattice. For  $\alpha \in I^1(E)$  we define  $\alpha L$  as the unique  $\mathbb{Z}G$ -lattice in  $V$  such that  $(\alpha L)_S = \alpha L_S$  and  $(\alpha L)_p = L_p$ . To show that  $\alpha L$  has discriminant  $p$ , it is enough to check that  $\alpha L_S$  is unimodular:

$$(\alpha L_S)_B^* = (\bar{\alpha})^{-1}(L_S)_B^* = (\bar{\alpha})^{-1}L_S = \alpha L_S$$

Since  $\alpha$  does not contain any ramification,  $\alpha$  is generated at a given prime  $\mathfrak{g}$  by an element  $a \in E_{\mathfrak{g}}$  satisfying  $a\bar{a} = 1$ . Therefore  $L$  and  $\alpha L$  belong to the same genus.

If  $L \cong \alpha L$ , there exists  $\alpha \in E$  such that  $\alpha\bar{\alpha} = 1$  and  $\alpha L = \alpha L$ . Thus  $\alpha O_S =$

$\alpha O_S$ . On the other hand, neither  $\alpha$  nor  $\alpha$  contain any ramification, therefore  $\alpha = \alpha O_E$ . Hence  $I^1(E)/P^1(E)$  acts freely on the classes.

b) Assume now that  $\text{End}_{\mathbb{Z}G}(L) = O_E$  and let  $L'$  be another lattice in the genus of  $L$ .

Observe first that  $L_p = L'_p$ : let  $a \in E_p = E_v$  such that  $a\bar{a} = 1$  and  $aL_p = L'_p$ . The isometry  $a$  is necessarily a  $\mathfrak{p}$ -unit, and, since  $L_p$  is preserved by  $O_{E_v}$ , we must have  $aL_p = L_p$ .

On the other hand, from the proof of Theorem 2.7, we know that there exist an  $S$ -ideal  $\alpha$  such that  $\alpha L_S = L'_S$ . But we also have  $L_p = L'_p$ , therefore  $\alpha L = L'$ . Thus  $I^1(E)$  acts transitively on the genus of  $L$ .  $\square$

(2.10) COROLLARY. a) *The number of classes in the genus of  $L$  is divisible by the relative class number  $h(E)/h(F)$  of  $E/F$ .*

b) *If in addition  $\text{End}_{\mathbb{Z}G}(L) = O_E$ , then the number of classes in the genus of  $L$  is equal to the relative class number  $h(E)/h(F)$ .*

*Proof.* I owe the following observation to P. Conner: let  $C(E)$  and  $C(F)$  denote the ideal class group of  $E$  and  $F$  respectively. Let  $N_{E/F}: C(E) \rightarrow C(F)$  be the norm map. We have an exact sequence

$$0 \rightarrow \hat{H}^0(\text{Gal}(E/F), C(E)) \xrightarrow{i} I^1(E)/P^1(E) \xrightarrow{\varphi} \text{Ker } N_{E/F} \xrightarrow{j} H^1(\text{Gal}(E/F), C(E)) \rightarrow 0$$

where  $\varphi$  is induced by the restriction of the canonical projection  $I(E) \rightarrow C(E)$ ; the homomorphism  $i$  is defined by  $i[\alpha] = [\alpha]$  and the homomorphism  $j$  is defined by  $j[b] = [b\bar{b}^{-1}]$ , the brackets being interpreted as classes in the appropriate group. The verification of exactness is routine. On the other hand, the Herbrand quotient of a finite module is equal to 1 (see [S], Chap. VIII Proposition 8), this applies in particular to  $C(E)$ . Hence, by exactness,  $I^1(E)/P^1(E)$  and  $\text{Ker } N_{E/F}$  have the same order. It is well known that  $N_{E/F}: C(E) \rightarrow C(F)$  is surjective (see for instance [W] Theorem 10.1); therefore  $[I^1(E):P^1(E)] = h(E)/h(F)$ . Corollary 2.10 follows immediately from Theorem 2.9 and this observation.  $\square$

*Remark.* The order of  $I^1(E)/P^1(E)$  was calculated with the help of the mass formula in [M] Corollary 3.10. E. Bayer carried out similar calculations for more general fields in [B1].

We want next to estimate the number of genera of maximal integral  $\mathbb{Z}G$ -lattices contained in  $V$ . In order to prove our main result in this direction (Theorem 2.12), we need the following technical lemma:



(2.11) LEMMA. Let  $\tau$  be a generator of  $C_p$  and  $T$  a  $\mathbb{F}_p C_p$ -module of dimension 3 over  $\mathbb{F}_p$  such that  $C_p$  preserves a nondegenerate quadratic form on  $T$ . Then either  $T$  is  $C_p$ -trivial or  $T$  is isomorphic to  $\mathbb{F}_p[t]/(t-1)^3$ , where the generator  $\tau$  of  $C_p$  acts by multiplication by  $t$ .

*Proof.* By the classification of the  $\mathbb{F}_p C_p$ -modules, we may assume that  $T^G$  has dimension at least 2 over  $\mathbb{F}_p$  (otherwise  $T$  would be indecomposable and therefore isomorphic to  $\mathbb{F}_p[t]/(t-1)^3$ ). Since in this case  $T^G$  cannot be totally isotropic, we choose an anisotropic vector  $x \in T^G$ . Thus we have an orthogonal decomposition

$$T \cong \mathbb{F}_p x \perp (\mathbb{F}_p x)^\perp$$

On the other hand,  $p$  does not divide the order of the orthogonal group of a quadratic form of rank 2 over  $\mathbb{F}_p$  (see [C] 1.4). Therefore, the second factor  $(\mathbb{F}_p x)^\perp$  is also  $C_p$ -trivial.  $\square$

(2.12) THEOREM. The following conditions are equivalent:

- a) All the maximal  $\mathbb{Z}G$ -lattices  $L \subset V$  satisfy  $H^1(G, L) \cong \mathbb{F}_p$
- b) There exists a maximal  $\mathbb{Z}G$ -lattice  $L \subset V$  such that  $H^1(G, L) \cong \mathbb{F}_p$
- c) All the maximal  $\mathbb{Z}G$ -lattices of  $V$  belong to the same equivariant genus

*Proof.* a)  $\Rightarrow$  b) is obvious.

b)  $\Rightarrow$  c). Let  $L \subset V$  be a maximal  $\mathbb{Z}G$ -lattice satisfying condition b). Let  $L'$  be another maximal  $\mathbb{Z}G$ -lattice. We know (proof of Theorem 2.7) that  $L$  and  $L'$  are ideal-equivalent over the  $S$ -integers  $O_S$ , that is, there is an  $S$ -ideal  $\alpha$  such that  $\alpha L'_S = L_S$ . It is easy to see that  $\alpha$  must verify  $\alpha \bar{\alpha} = O_S$  and to check that  $L'_q \cong L_q$  for all  $q \neq p$ . It is then enough to prove that  $L_p$  is the only maximal  $\mathbb{Z}_p G$ -lattice in  $V_p$ .

We have  $H^1(G, L) = (V/L)^G$  from the cohomology exact sequence associated to  $0 \rightarrow L \rightarrow V \rightarrow V/L \rightarrow 0$ . On the other hand,  $(V/L)^G = (I_G L^*)^*/L$ , where  $I_G$  is the augmentation ideal of  $\mathbb{Z}G$ . Thus  $L^*/I_G L^*$  is canonically identified with the character group of  $H^1(G, L)$ , which is by hypothesis isomorphic to  $\mathbb{F}_p$ . Therefore  $I_G L^*$  has index  $p$  in  $L^*$ .

By connectivity of the graph of lattices in  $V_p$  (Theorem 1.4 is clearly also valid locally), we may assume  $\delta(L'_p, L_p) \leq 1$ . With this hypothesis we have  $I_G L_p^* \subset L_p^*$ . Since  $I_G L_p^*$  is contained in  $L_p$  and has index  $p$  in  $L^*$ , we have  $I_G L_p^* = L_p$ . Therefore  $L_p \subset L_p^*$ . By maximality of  $L'_p$ , we conclude  $L_p \subset L'_p$  and by maximality of  $L_p$  we get the equality  $L_p = L'_p$ .

c)  $\Rightarrow$  b). Suppose that for all maximal  $\mathbb{Z}G$ -lattices  $L$  we have  $|H^1(G, L)| \geq p^2$ .

Let  $L$  be a maximal  $O_E G$ -lattice. Then there exists a  $O_E G$ -lattice  $M$  with  $I_G L^* \subset M \subset L$  and  $[M:L] = p$ . We will show that  $M^*/M$  is a trivial  $\mathbb{Z}G$ -module. We have

$$I_G M^* \subset I_G (I_G L^*)^* \subset L$$

Therefore the order of  $(M^*/M)^G$  is at least  $p^2$ . Let  $\xi$  be a generator of the image of  $Z(G)$  in  $E$ , which is a nontrivial root of 1. We have

$$pM^* \subset (\xi - 1)^2 M^* \subset I_G^2 M^* \subset I_G L \subset M.$$

Therefore  $T := M^*/M$  is a  $\mathbb{F}_p G$ -module of dimension 3. It is well known from the order of the finite classic groups (see for instance [C] 1.4) that the  $p$ -subgroup of the orthogonal group of a quadratic form of rank 3 over  $\mathbb{F}_p$  is cyclic of order  $p$ . Hence the action of  $G$  on  $T$  factors through a cyclic quotient of order  $p$  of  $G$ . According to Lemma 2.11, since  $\dim_{\mathbb{F}_p}(T^G) \geq 2$  and  $T$  has a quadratic form preserved by  $G$ ,  $T$  must be  $G$ -trivial. A quadratic space of dim 3 over  $\mathbb{F}_p$  has  $(p+1)$  isotropic sub-spaces of dimension 1, each one of them corresponding to a maximal lattice  $N$  with  $M \subset N \subset M^*$ . They belong indeed to different genera.

c)  $\Rightarrow$  a). The cohomology  $H^*(G, L)$  depends only on the local component  $L_p$  of  $L$ . It is therefore in particular an invariant of the genus of  $L$ . On the other hand, according to c)  $\Rightarrow$  b), we know that  $H^1(G, L) = \mathbb{F}_p$  for some maximal  $\mathbb{Z}G$ -lattice  $L$ .  $\square$

(2.13) COROLLARY. *If  $G$  is cyclic, then  $V$  contains only one genus of maximal  $\mathbb{Z}G$ -lattices.*

*Proof.* In this case  $V$  has dimension 1 over  $E$  and a  $\mathbb{Z}G$ -lattice  $L$  in  $V$  can be identified with an ideal of  $E$ . Let  $\xi \in E$  be the image in  $E$  of a generator of  $G$ . Clearly  $\xi$  is a root of 1 and generates  $E$  over  $\mathbb{Q}$ . Then we have  $H^1(G, L) = L/(\xi - 1)L \cong \mathbb{F}_p$ . We apply Theorem 2.12.  $\square$

(2.14) LEMMA. *Let  $H$  be the group  $C_p \times C_p$  with generators  $x$  and  $y$ . Let  $G$  be the semi-direct product  $G = C_p \tilde{\times} (C_p \times C_p)$  which admits a presentation*

$$G = \langle x, y, t \mid x^p = y^p = t^p = [x, y] = [x, t] = 1, \quad [t, y] = x \rangle$$

*Let  $E$  be the cyclotomic field  $\mathbb{Q}(\zeta_p)$  and  $U$  be the representation of  $H$  over  $\mathbb{Q}$  defined by  $U = E$  as a  $\mathbb{Q}$ -vector space and  $xu = \zeta_p u$  and  $yu = u$ . Then the induced representation  $V = \text{Ind}_H^G(U)$  is simple and is the only nonabelian simple repre-*

sensation of  $G$  (by nonabelian representation we mean a representation on which the commutator subgroup  $[G, G]$  does not act trivially).

*Proof.* By definition  $V$  has a decomposition

$$V = U \oplus tU \oplus \cdots \oplus t^{p-1}U.$$

It is easy to check that  $t^i U$  and  $t^j U$  are nonisomorphic simple  $\mathbb{Q}H$ -modules for  $i \neq j$ . Thus, by Frobenius Reciprocity, we obtain

$$\text{End}_G(V) \cong \text{Hom}_H(U, V) \cong E$$

Therefore  $V$  is simple. By Wedderburn's Theorem, the algebra  $\mathbb{Q}G^{ab} \times M_p(E)$  splits off the group algebra  $\mathbb{Q}G$ . It is easy to check from the presentation of  $G$  that  $G^{ab} \cong C_p \times C_p$ . Thus both  $\mathbb{Q}G^{ab} \times M_p(E)$  and  $\mathbb{Q}G$  have dimension  $p^3$  over  $\mathbb{Q}$  and therefore are equal. Hence  $V$  is the only nonabelian simple representation of  $G$ . It can also be checked that  $V$  is faithful.  $\square$

(2.15) PROPOSITION. *Let  $G$  and  $V$  as in Lemma 2.14 and let  $B: V \times V \rightarrow \mathbb{Q}$  be a  $G$ -invariant form. Then  $V$  contains only one genus of maximal  $\mathbb{Z}G$ -lattices for  $p = 3$  and  $V$  contains at least  $(p + 1)$  distinct genera of maximal  $\mathbb{Z}G$ -lattices for  $p \geq 5$ .*

*Proof.* Let  $U$  be the  $\mathbb{Q}H$ -module defined in Lemma 2.14. Clearly the decomposition  $V = U \oplus tU \oplus \cdots \oplus t^{p-1}U$  is orthogonal. Let  $L \subset U$  be a maximal  $\mathbb{Z}H$ -lattice and  $M \supset \text{Ind}_H^G(L)$  be a maximal  $\mathbb{Z}G$ -lattice of  $V$ . By Theorem 2.12, it will be enough to prove that  $H^1(G, M) = \mathbb{F}_p$  for  $p = 3$  and  $H^1(G, M) = \mathbb{F}_p \oplus \mathbb{F}_p$  for  $p \geq 5$ .

Let  $N = \text{Ind}_H^G(L)$  and consider the following cohomology diagram associated to the chain  $N \subset M \subset M^* \subset N^*$

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & \\
 & & \downarrow & & \downarrow & & \\
 & & (N^*/M)^G & = & (N^*/M)^G & & \\
 & & \downarrow & & \downarrow & & \\
 0 \longrightarrow & (M/N)^G & \longrightarrow & H^1(G, N) & \longrightarrow & H^1(G, M) & \longrightarrow & H^1(G, M/N) & \longrightarrow & H^2(G, N) \\
 & \parallel & & \parallel & & \downarrow & & \downarrow & & \parallel \\
 0 \longrightarrow & (N^*/N)^G & \longrightarrow & H^1(G, N) & \longrightarrow & H^1(G, N^*) & \longrightarrow & H^1(G, N^*/N) & \longrightarrow & H^2(G, N)
 \end{array}$$

Note that by construction  $(N^*/N)_p \cong \text{Ind}_H^G (L^*/L)_p \cong \text{Ind}_H^G (\mathbb{F}_p) \cong \mathbb{F}_p G/H \cong \mathbb{F}_p C_p$ . Thus  $(M/N)_p^G = (N^*/N)_p^G = \mathbb{F}_p$ . On the other hand we have  $H^1(G, N) \cong H^1(H, L)$  (see [S] Chap. V Section 5). A straightforward computation shows  $H^1(H, L) \cong (\xi_p - 1)^{-1} L/L \cong \mathbb{F}_p$ . Similarly  $H^1(G, N^*) \cong H^1(H, L^*) \cong \mathbb{F}_p$ . Thus we have a simplified diagram

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & \\
 & & \downarrow & & \downarrow & & \\
 & & \mathbb{F}_p & = & \mathbb{F}_p & & \\
 & & \downarrow & & \downarrow & & \\
 0 & \longrightarrow & H^1(G, M) & \longrightarrow & H^1(G, M/N) & \longrightarrow & H^2(G, N) \\
 & & \alpha \downarrow & & \beta \downarrow & & \parallel \\
 0 & \longrightarrow & \mathbb{F}_p & \longrightarrow & H^1(G, N^*/N) & \longrightarrow & H^2(G, N).
 \end{array}$$

We will show that  $\beta$  is surjective for  $p \geq 5$ . It will follow from the diagram that  $\alpha$  is also surjective. We consider the following inflation-restriction sequences (see [S] Chap. VII Section 6)

$$\begin{array}{ccccccc}
 0 & \longrightarrow & H^1(G/H, M/N) & \xrightarrow{\text{inf}} & H^1(G, M/N) & \xrightarrow{\text{res}} & H^1(H, M^*/N)^{G/H} \\
 & & & & \beta \downarrow & & \gamma \downarrow \\
 & & & & H^1(G, N^*/N) & \xrightarrow{\text{res}} & H^1(H, N^*/N)^{G/H}
 \end{array}$$

To show that  $\beta$  is surjective, it is enough to show that  $\gamma$  is surjective. The subgroup  $H$  acts trivially on both  $M_p/N_p$  and  $N_p^*/N_p$ , therefore

$$\begin{aligned}
 H^1(H, M/N)^{G/H} &= \text{Hom}_{G/H}(H, M/N) \\
 H^1(H, N^*/N)^{G/H} &= \text{Hom}_{G/H}(H, N^*/N).
 \end{aligned}$$

Let  $\tau$  be a generator of  $C_p \cong G/H$ . We have the following isomorphisms of  $\mathbb{F}_p G/H$ -modules

$$\begin{aligned}
 H &\cong \mathbb{F}_p[t]/(t-1)^2 \\
 M_p/N_p &\cong \mathbb{F}_p[t]/(t-1)^{(p-1)/2} \\
 N_p^*/N_p &\cong \mathbb{F}_p[t]/(t-1)^p,
 \end{aligned}$$

where the generator  $\tau$  acts by multiplication by  $t$ .

Thus the equality

$$\mathrm{Hom}_{G/H}(H, M/N) = \mathrm{Hom}_{G/H}(H, N^*/N)$$

holds provided  $(p-1)/2 \geq 2$ . Hence  $\beta$  and  $\alpha$  are surjective for  $p \geq 5$  and  $H^1(G, L) \cong \mathbb{F}_p \oplus \mathbb{F}_p$ .

The case  $p=3$  requires a special consideration. We put  $\Pi = \zeta_3 - 1$  and consider the exact sequence

$$0 \longrightarrow M \xrightarrow{\Pi} M \longrightarrow M/\Pi M \longrightarrow 0$$

which induces a natural isomorphism  $(M/\Pi M)^G \xrightarrow{\cong} H^1(G, M)$ . We will compute the group  $(M/\Pi M)^G$ .

By construction  $N_p^* \cong O_{E_p}^3$  where the coordinates are permuted cyclically by  $\tau$ . Indeed  $M_p$  is the inverse image of  $(N_p^*/N_p)^G$  in  $N_p^*$ . Therefore  $M_p$  is generated over  $O_{E_p}$  by the vectors

$$(1, 1, 1); \quad (0, \Pi, 0); \quad (0, 0, \Pi)$$

The matrix of  $t$  in this basis is

$$T = \begin{bmatrix} 1 & 0 & \Pi \\ 0 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix}$$

It is elementary to check that the reduction modulo  $\Pi$  of  $(T-1)$  has rank 2 over  $\mathbb{F}_3$ . Therefore

$$H^1(G, M) \cong (M/\Pi M)^G \cong \mathrm{Ker}(T-1) \cong \mathbb{F}_3. \quad \square$$

## Acknowledgement

The work that has led to this paper began while the author was visiting the University of Goettingen, West Germany, the year 84/85, supported by a post-doctoral fellowship of the Fonds National de la Recherche Scientifique (Switzerland). The author thanks both institutions and his host Professor Martin Kneser.

I am particularly grateful to Professor Pierre Conner whose comments made it possible to give much clearer formulations of many results in Section 2. Special thanks go also to Professor Robert Perlis for his many useful observations.

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Received August 10, 1986