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A uniform bound for the order of monodromy

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For a compatible system of ℓ-adic Galois representations with some condition, the elements of inertia acting unipotently constitutes an open subgroup. We give an explicit bound for the index of this subgroup, which is independent of ℓ. For the etale cohomology of a smooth projective variety, we give a bound of the index acting unipotently on the all degree of cohomology groups. This bound depends only on some numerical invariants of the variety such as Betti numbers and this is independent of ℓ.

1. Introduction

Let K be a complete discrete valuation field, let k be the residue field of K and p be the characteristic of k. Let ℓ be a prime number distinct from p. Let G_K be the absolute Galois group $\mathrm{Gal}(K^{sep}/K)$ and I_K be the inertia group of K.

For an ℓ-adic Galois representation of G_K, Grothendieck's monodromy theorem is a fundamental result.

Theorem 1 ([7], Appendix). *Let ρ be an ℓ-adic representation of G_K and k satisfy the following property:*

(C_ℓ) No finite extension of k contains all the roots of unity of ℓ-power order.

Then there exists an open subgroup H of I_K such that $\rho(s)$ is unipotent for all $s \in H$.

In [1, Exposé I, 1.3], he also proves this theorem without the assumption (C_ℓ) if ρ occurs as the ℓ-adic etale cohomology group of a scheme of finite type over a henselian discrete valued field.

For a profinite group, an open subgroup has finite index. In this paper, we discuss this index. More precisely, if the representation appears as the ℓ-adic etale cohomology of an algebraic variety over K, we can compute a bound for the index which is uniform on X and independent of ℓ by using some explicit numerical invariants.

The statement is the following.

Theorem 2. *Let the residue field k of K be a perfect field and satisfy (C_ℓ) for every prime $\ell \neq p$. Let n be a positive integer, $b \in \mathbb{N}^n$ and $c \in \mathbb{Z}^{n-1}$. The constant $D_{b,c,n}$ (defined in Definition 2) satisfies the following property:*

For a smooth projective geometrically connected variety X of dimension n over K, a very ample invertible sheaf L on X with $(b_i(X))_{i=1,\dots,n} = b$ and $(c_i(X, L))_{i=1,\dots,n-1} = c$, there exists an open subgroup I of I_K of index $[I_K : I]$ dividing $D_{b,c,n}$ such that the action of I on $H^i(X_{\bar{K}}, \mathbb{Q}_\ell)$ is unipotent for every i and every ℓ.

Here, $b_i(X)$ is the i-th Betti number of X and $c_i(X, L)$ is a certain Chern characteristic. (See Definition 1.)

In [3, Proposition 6.3.2], Berthelot shows the existence of a subgroup which is independent of ℓ by using an alteration under more general assumption. In fact, he assume neither X is proper nor smooth. He does not assume that k satisfies (C_ℓ). In this paper, we show that the index is not only independent of ℓ but also bounded uniformly on X.

If the number of field extensions (up to isomorphism) of K whose degree is bounded is finite, then our theorem asserts that the existence of a subgroup which depends only on the numerical invariants $b_i(X)$ and $c_i(X, L)$ of X and it is independent of X, L and ℓ. A finite extension K of $\mathbb{Q}_p$ satisfies this assumption.

The content of this paper is the following. In section 2, we give a bound for the index in the case of a compatible system of ℓ-adic representations. In section 3, we apply it to the case of the etale cohomology of a variety and prove the theorem. For the proof, we reduce it to the case of a compatible system by using induction and an ℓ-independence result of Ochiai [6, Theorem 2.4].

We say that a representation of a topological group G is an ℓ-adic representation if it is a continuous linear representation on a finite dimensional vector space over $\mathbb{Q}_\ell$.

2. Compatible system

In this section, we discuss a bound for a compatible system. This will immediately imply the $n = 1$ case of our theorem.

First, we define constants $C_{\ell,d}$ and C_d for a non negative integer d and a prime number ℓ. The constant $C_{\ell,d}$ denotes the order of the finite group $GL_d(\mathbb{F}_\ell)$ if ℓ is not equal to 2 and $GL_d(\mathbb{Z}/4\mathbb{Z})$ if ℓ is equal to 2. Expilicitly,

$$C_{\ell,d} = \begin{cases} \ell^{\frac{d(d-1)}{2}} \prod_{k=1}^{k=d}(\ell^k - 1) & \ell \neq 2 \\ 2^{d^2+\frac{d(d-1)}{2}} \prod_{k=1}^{k=d}(2^k - 1) & \ell = 2 \end{cases}$$

The constant C_d denotes $\gcd(C_{\ell,d} \mid \ell \neq p)$, which can be explicitly computed as follows. For each odd prime number q, we can choose a prime number ℓ which is a generator of $(\mathbb{Z}/q^i\mathbb{Z})^*$ for a sufficiently large i. For $q = 2$, we can take a prime number ℓ which is an element of order 2^{i-2} of $(\mathbb{Z}/2^i\mathbb{Z})^*$ for sufficiently large i. Put

$$r_q = \begin{cases} \sum_{i\geq 0} \lfloor \frac{d}{(q-1)q^i} \rfloor & q \neq 2 \\ \lfloor \frac{d}{2} \rfloor + \sum_{i\geq 0} \lfloor \frac{d}{(q-1)q^i} \rfloor & q = 2 \end{cases}$$

and we have $C_d = \prod_q q^{r_q}$. In particular, this does not depend on p. We use these constants in the definition of the constant $D_{b,c,n}$ in Definition 2.

Proposition 1. *Let ℓ be a prime number not equal to p. Let (ρ, V) be an ℓ-adic representation of G_K with $\dim V = d$. Assume that the residue field k satisfies (C_ℓ). Then the subset $I = \{s \in I_K \mid \rho(s) \text{ is unipotent}\}$ of I_K is an open subgroup of I_K and the index $[I_K : I]$ divides $C_{\ell,d}$.*

This is a refinement of Theorem 1 proved by Grothendieck in [7, Appendix]. See also Deligne [4, Théorème 8.2].

Before proving this proposition, we review the proof of Theorem 1. By taking an appropriate basis of V, we may assume that the image of ρ is contained in a lattice $L \cong \mathbb{Z}_\ell^d$ of V. Put $I_\ell = I_K \cap \rho^{-1}(1 + \ell M_d(\mathbb{Z}_\ell))$ (resp. $I_K \cap \rho^{-1}(1 + 4M_d(\mathbb{Z}_2))$ if $\ell = 2$). This is an open subgroup of I_K.

The key step is to show that if $\rho(s)$ is contained in $1 + \ell^2 M_d(\mathbb{Z}_\ell)$ for $s \in I_K$, then it is unipotent. For $\ell \neq 2$, it is enough to be contained in $1 + \ell M_d(\mathbb{Z}_\ell)$. This shows that there is an open subgroup of I_K whose action on V is unipotent and all the eigenvalues of $s \in I_K$ are roots of unity.

We remark that without (C_ℓ) but assuming that the restriction of ρ to I_K is quasi-unipotent, I is still an open subgroup of I_K.

Proof. First, consider the case that the image of ρ is finite. If $X \in M_d(\mathbb{Q}_\ell)$ is unipotent and of finite order, then it is trivial. Hence, $\ker(\rho)$ is equal to the subset of unipotent elements.

The general case is reduced to the case of finite image as follows.

Take a continuous surjection $t : I_K \to \mathbb{Z}_\ell$ and an element $s_0 \in I_\ell$ such that $t(s_0) \neq 0$. Then $\rho|_{I_\ell}$ factors through this t and $\tilde{\rho} : \mathbb{Z}_\ell \to GL_n(\mathbb{Z}_\ell)$ because the image $\rho(I_\ell)$ is pro-ℓ and $\ker t$ is prime to ℓ. Put $N = t(s_0)^{-1} \log(\rho(s_0))$ and $r(s) = \rho(s) \exp(-t(s)N)$. Since $\rho(s_0) \in 1 + \ell M_d(\mathbb{Z}_\ell)$ is unipotent, N is nilpotent.

We claim that $\rho(s)$ and $\exp(-t(s)N)$ commute. In fact, $\rho(ss_0s^{-1}) = \tilde{\rho}(t(ss_0s^{-1})) = \tilde{\rho}(t(s_0)) = \rho(s_0)$. Hence, the map r is group homomorphism and $\mathrm{Tr}(r(s)) = \mathrm{Tr}(\rho(s))$. Since the unipotnence of $X \in M_d(\mathbb{Q}_\ell)$ is equivarent to $\mathrm{Tr}X = d$, this implies that $r(s)$ is unipotent if and only if $\rho(s)$ is unipotent. The image of r is finite because $r(s) = 1$ for $s \in I_\ell$.

Finally, we show the assertion about the index. In fact, I contains I_ℓ and so $[I_K : I]$ divides $[I_K : I_\ell]$. For $\ell \neq 2$, the subgroup $1 + \ell M_d(\mathbb{Z}_\ell)$ is the kernel of the natural map $GL_d(\mathbb{Z}_\ell) \to GL_d(\mathbb{F}_\ell)$. This implies that the induced map $I_K/I_\ell \to GL_d(\mathbb{F}_\ell)$ is injective and the index $[I_K : I_\ell]$ divides $C_{\ell,d}$. The same argument works for $\ell = 2$. □

When K is a non-archmedean local field, Deligne defined the Weil-Deligne representation (r_ρ, N_ρ) associated to ρ. See [4, Définition 8.4.1]. The r in the proof is the restriction of this r_ρ to the inertia group and the nilpotent operator N_ρ is the same operator.

As a corollary of this proposition, we get the following, which is a key step of the proof of the theorem.

Corollary 1. *Assume that the residue field k satisfies (C_ℓ) for every prime $\ell \neq p$. Let $\{(\rho_\ell, V_\ell)\}_{\ell \neq p}$ be a family of ℓ-adic representations of G_K such that $\mathrm{Tr}(\rho_\ell(s); V_\ell) = \mathrm{Tr}(\rho_{\ell'}(s); V_{\ell'}) \in \mathbb{Q}$ for every ℓ, ℓ' and $s \in I_K$. Set $d = \dim V_\ell$.*

Then the subgroup $I = \{s \in I_K \mid \rho_\ell(s)$ is unipotent$\}$ is independent of ℓ and the index $[I_K : I]$ divides C_d.

In the rest of this section, we discuss on the improvement of this bound. We claim that I_K/I is an extension of a p-prime cyclic group of order n satisfying $\varphi(n) \leq d$ by a p-group under the conditions that the restriction of ρ_ℓ to I_K are quasi-unipotent and the traces are ℓ-independent rational numbers without assuming (C_ℓ).

The proof of the proposition provides a faithful representation of I_K/I. The order n of $\rho_\ell(s)$ of $s \in I_K$ satisfies $\varphi(n) = \#(\mathbb{Z}/n\mathbb{Z})^* \leq d$. It follows that I_K/I is the extension of a p-prime cyclic group of order $n \leq A_{d,p} = \max\{k \mid p \nmid k, \varphi(k) \leq d\}$ by a p-group.

If we assume (C_ℓ) for all but finitely many prime ℓ, then we can bound the p-part of the constant. Then $[I_K : I] \leq B_{d,p} = p^{r_p} A_d$. This refines the bound

$C_d = \prod_q q^{r_q}$. Put $A_{d,p} = \prod_q q^{a_q}$. The order of the group $(\mathbb{Z}/A_{d,p}\mathbb{Z})^*$ satisfies that $(\mathbb{Z}/A_{d,p}\mathbb{Z})^* = \prod_q (\mathbb{Z}/q^{a_q}\mathbb{Z})^* \leq d$. Hence, we have $a_q - 1 \leq \log_q \frac{d}{q-1}$ and this implies $a_q \leq r_q$. We note that this $B_{d,p}$ depends on the residual characteristic p and it does not follow that $[I_K : I]$ divides $B_{d,p}$.

3. Proof of the theorem

In this section, we prove the theorem. First, we introduce some numerical invariants to compute the bound.

Definition 1. Let X be a smooth projective variety over a separably closed field k of dimension n, L a very ample invertible sheaf on X and $\ell \neq char(k)$ a prime number. We define numerical invariants $b_i(X)$ and $c_i(X, L)$ as follows.

$$b_i(X) = \dim H^i(X, \mathbb{Q}_\ell)$$
$$c_i(X, L) = f_*(c(\check{\Omega}^1_X)c(L)^{-i}c_1(L)^i).$$

Here, $c_i(E) \in H^{2i}(X, \mathbb{Q}_\ell(i))$ is the i-th Chern class and $c(E) \in \oplus_{i=0}^{\dim X} H^{2i}(X, \mathbb{Q}_\ell(i))$ is the total Chern class of a locally free sheaf E. The map f is the structure map of X and $f_* : \oplus_{i=0}^{\dim X} H^{2i}(X, \mathbb{Q}_\ell(i)) \to H^0(\mathrm{Spec}(k), \mathbb{Q}_\ell) = \mathbb{Q}_\ell$ is the Gysin morphism.

These numbers are integers and independent of ℓ. (See [5, 1.4] for $b_i(X)$. The ℓ-independence of $c_i(X, L)$ follows by the intersection theory.)

For a variety X over k and a very ample invertible sheaf L on X, a j-hyperplane section means an iterated hyperplane section $X_j = X \cap H_1 \cap \cdots \cap H_j$ of X of codimension j, here H_i is a hyperplane defined by L.

Lemma 1 ([2], Exposé VII, Proposition 7.3). *Let X be a smooth projective connected scheme over a separably closed field of dimension n and L a very ample invertible sheaf on X. Take a smooth j-hyperplane section X_j of X defined by L. Then*

$$c_j(X, L) = \sum_i (-1)^i b_i(X_j) \tag{1}$$

$$b_{n-j}(X_j) = (-1)^{n-j} \left(c_j(X, L) - 2 \sum_{i=0}^{n-j-1} (-1)^i b_i(X) \right) \tag{2}$$

and it does not depend on the choice of hyperplane section.

Proof. By the weak Lefschetz theorem and Poincaré duality, $b_i(X) = b_i(X_j) = b_{2n-2j-i}(X_j)$ if $i \leq n-j-1$. Therefore, the second equation follows from the first one. $\square$

Definition 2. Let n be a positive integer, $b = (b_1, \ldots, b_n)$ an n-tuple of non-negative integers and $c = (c_1, \ldots, c_{n-1})$ an $n-1$-tuple of integers. We define an n-tuple of integers $d_{b,c} = (d_{b,c,1}, \ldots, d_{b,c,n})$ as follows.

$$d_{b,c,j} = \begin{cases} (-1)^j \left(c_{n-j} - 2\sum_{i=0}^{j-1}(-1)^i b_i\right) & j \neq n \\ b_j & j = n \end{cases}$$

We define the constant $D_{b,c,h}$ for a positive integer $h \leq n$, $b \in \mathbb{N}^n, c \in \mathbb{Z}^{n-1}$ for which the all $d_{b,c,1}, \ldots d_{b,c,h}$ are nonnegative.

$$D_{b,c,h} = \prod_{j=1}^{h} C_{d_{b,c,j}}.$$

Here $C_{d_{b,c,j}}$ is the constant defined in the beginning of the previous section.

If X and L satisfies $b_i(X) = b_i$ and $c_i(X, L) = c_i$ for all i, $d_{b,c,j}$ is the middle Betti number $b_j(X_{n-j})$ of a smooth $(n-j)$-hyperplane section X_{n-j} of X.

Now we prove theorem 2 stated in the introduction.

Theorem 2. *Let the residue field k of K be a perfect field and satisfy (C_ℓ) for every prime $\ell \neq p$. Let n be a positive integer, $b \in \mathbb{N}^n$ and $c \in \mathbb{Z}^{n-1}$. The constant $D_{b,c,n}$ (defined in Definition 2) satisfies the following property:*

For a smooth projective geometrically connected variety X of dimension n over K, a very ample invertible sheaf L on X with $(b_i(X))_{i=1,\ldots,n} = b$ and $(c_i(X, L))_{i=1,\ldots,n-1} = c$, there exists an open subgroup I of I_K of index $[I_K : I]$ dividing $D_{b,c,n}$ such that the action of I on $H^i(X_{\bar{K}}, \mathbb{Q}_\ell)$ is unipotent for every i and every ℓ.

Proof. We prove this theorem by induction on n.

Case $n = 1$. In this case, the theorem is essentially proved in section 2. If X is a curve, I_K acts trivially on $H^0(X_{\bar{K}}, \mathbb{Q}_\ell) \cong \mathbb{Q}_\ell$ and $H^2(X_{\bar{K}}, \mathbb{Q}_\ell) \cong \mathbb{Q}_\ell(-1)$. Since $H^1(X_{\bar{K}}, \mathbb{Q}_\ell)$ is equal to the Tate module of Albanese variety of X and the ℓ-independence of the trace of the Tate module of an abelian variety is proved in [1, Exposé IX, Theorem 4.3], we get the ℓ-independence of the trace of $H^1(X_{\bar{K}}, \mathbb{Q}_\ell)$. By applying Corollary 1 to $H^1(X_{\bar{K}}, \mathbb{Q}_\ell)$, we get the result.

Case general n. Assume that for all $k < n$, $b \in \mathbb{N}^k$ and $c \in \mathbb{Z}^{k-1}$, the constant $D_{b,c,k}$ satisfies the property of the theorem. Take $b \in \mathbb{N}^n$ and $c \in \mathbb{Z}^{n-1}$. Let X be a variety and L a very ample invertible sheaf satisfying the assumption of the theorem.

Step 1. First, we show that there exists an open subgroup J such that the action on $H^i(X_{\bar{K}}, \mathbb{Q}_\ell)$ for $i \neq n$ and every ℓ is unipotent and the index divides $D_{b,c,n-1}$.

By the Bertini theorem, there exists a smooth hyperplane section of X defined by a section of L. Take such a hyperplane section Y. Then $L|_Y$ is a very ample invertible sheaf on Y. Put $\tilde{b} = (b_i(Y))_{i=1,\dots,n-1}$ and $\tilde{c} = (c_i(Y, L|_Y))_{i=1,\dots,n-2}$. By the induction assumption, there exists an open subgroup J of I_K whose index divides $D_{\tilde{b},\tilde{c},n-1}$ and the action on $H^i(Y_{\bar{K}}, \mathbb{Q}_\ell)$ is unipotent for all i and all ℓ.

We claim that $D_{\tilde{b},\tilde{c},n-1} = D_{b,c,n-1}$. By Lemma 1, $d_{b,c,j}$ is the middle Betti number of an $(n-j)$-hyperplane section of X and $d_{\tilde{b},\tilde{c},j}$ is that of an $(n-j-1)$-hyperplane section of Y. Because this is independent of the choice of a hyperplane section, $d_{b,c,j} = d_{\tilde{b},\tilde{c},j}$ and the claim holds.

By the weak Lefschetz theorem, the restriction map $H^i(X_{\bar{K}}, \mathbb{Q}_\ell) \to H^i(Y_{\bar{K}}, \mathbb{Q}_\ell)$ is injective for $i \leq n-1$. Hence the action of J on $H^i(X_{\bar{K}}, \mathbb{Q}_\ell)$ is unipotent for $i \leq n-1$. By the Poincaré duality, the action of J on $H^i(X_{\bar{K}}, \mathbb{Q}_\ell)$ is also unipotent for $i \geq n+1$.

Step 2. We show that there exists an open subgroup I of I_K such that the action on $H^n(X_{\bar{K}}, \mathbb{Q}_\ell)$ is unipotent for every ℓ and that the index divides $D_{b,c,n}$.

By the previous step it follows that for $i \neq n$ and $s \in J$,

$$\mathrm{Tr}(s; H^i(X_{\bar{K}}, \mathbb{Q}_\ell)) = b_i$$

and this trace is independent of ℓ.

By a theorem of Ochiai [6, Theorem 2.4], the alternating sum

$$\sum_{i=0}^{2n} (-1)^i \mathrm{Tr}(s; H^i(X_{\bar{K}}, \mathbb{Q}_\ell))$$

is independent of ℓ for $s \in I_K$. Hence the trace $\mathrm{Tr}(s; H^n(X_{\bar{K}}, \mathbb{Q}_\ell))$ is independent of ℓ for $s \in J$.

We take a finite extension L over K such that the inertia group I_L equals to J. By applying Corollary 1 to $\rho|_{G_L}$, there exists an open subgroup $I \subset J$

such that the action of I is unipotent on $H^n(X_{\bar{K}}, \mathbb{Q}_\ell)$ and $[J : I] | C_{b_n}$. Also the action on $H^i(X_{\bar{K}}, \mathbb{Q}_\ell)$ $i \neq n$ is unipotent and the index $[I_K : I]$ divides $D_{b,c,n-1} C_{b_n} = D_{b,c,n}$. □

We give a few remarks on this theorem.

If K is a finite extension of $\mathbb{Q}_p$, then the action of this I on $H^i(X_{\bar{K}}, \mathbb{Q}_p)$ is potentially semi-stable. In his paper [6], Ochiai shows equality of the alternating sum of traces of $H^i(X_{\bar{K}}, \mathbb{Q}_\ell)$ and $D_{pst}(H^i(X_{\bar{K}}, \mathbb{Q}_p))$. If F is a number field, we can show that there exists a uniform bound for the index in similar way. There exists a constant C depending on some b, c and n such that for every smooth projective variety X over F and very ample line bundle H with $\dim X = n, b(X) = b$ and $c(X, H) = c$, there exists a finite extension E of F of $[E : F] < C$ such that the action of $\mathrm{Gal}(\bar{E}_v/E_v)$ on $H^i(X_{\bar{F}}, \mathbb{Q}_\ell)$ is unipotent at $v \nmid \ell$ and semi-stable at $v \mid \ell$. By the theorem of Hermite-Minkowski, if we fix the finite set S of finite places of F, then there exists a finite extension E/F such that for every smooth projective variety X over F which has good reduction outside S every local representation $\mathrm{Gal}(\bar{E}_v/E_v)$ becomes unipotent or semi-stable.

It is natural to ask whether the bound in the theorem is strict. On the middle cohomology, there is the bilinear form defined by the Poincaré duality. The action of Galois group preserves the bilinear form. Hence, we can define new constants using the order of the orthogonal group or symplectic group of the bilinear form instead of the constants C_d and $B_{d,p}$ which uses the order of GL.

Even if we refine the constants as above, this is not strict. In [8], Silverberg and Zarhin classifies the finite groups which appear as the inertia subgroup of an abelian surfaces. Their classification is purely group theoretic and they construct an abelian surface whose inertia is the group for all the groups appearing in the classification. For $p = 2$, the greatest common divisor of the order $\mathrm{Sp}_4(\mathbb{F}_\ell)$ is 128 and $A_{4,2}$ is 5. Hence $B_{4,2} = 640$ but the maximum of the order of the group appears in their classification is 384.

If we know the ℓ-independence of the trace of individual cohomology H^i, then we get a bound only using the compatible system case and does not need the discussion using Lefshetz hyperplane section.

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