WEIL NUMBERS GENERATED BY OTHER WEIL NUMBERS AND TORSION FIELDS OF ABELIAN VARIETIES

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Abstract. Using properties of the Frobenius eigenvalues, we show that, in a precise sense, “most” isomorphism classes of (principally polarized) simple abelian varieties over a finite field are characterized, up to isogeny, by the sequence of their division fields, and a similar result for “most” isogeny classes. Some global cases are also treated.

1. Introduction

Let \( q = p^k \) be a power of a prime number and let \( \pi \) be a \( q \)-Weil number, i.e., an algebraic integer such that for every automorphism \( \sigma \) of \( \mathbb{C} \) we have \(|\sigma(\pi)| = \sqrt{q}\). Let \( \Phi_\pi \) be the multiplicative group generated inside \( \mathbb{C}^\times \) by the Galois-conjugates of \( \pi \). We are interested in the multiplicative group structure of \( \Phi_\pi \) and particularly in the set (say \( w_\pi \)) of \( q \)-Weil numbers inside \( \Phi_\pi \). Clearly, \( w_\pi \) contains all the conjugates of \( \pi \), and we wish to know when there is equality.

Our motivation relates to abelian varieties over finite fields. Let \( A/\mathbb{F}_q \) be such an abelian variety over a field with \( q \) elements. Weil proved that all eigenvalues of the Frobenius endomorphism \( \pi_A \) of \( A \) are \( q \)-Weil numbers. We denote by \( \Phi_A \) the multiplicative group that they generate. If \( A \) is simple, then \( \pi_A \) “is” an algebraic integer and \( \Phi_A = \Phi_{\pi_A} \). We also denote by \( w_A \) the set of \( q \)-Weil numbers in \( \Phi_A \).

In [K1, Th. 3.4], it is shown that given abelian varieties \( A/\mathbb{F}_q \) and \( B/\mathbb{F}_q \), the condition \( \Phi_A = \Phi_B \) is equivalent with the fact that, for all \( n \) coprime with some integer \( N \) (which may depend on \( A \) and \( B \)), we have \( \mathbb{F}_q(A[n]) = \mathbb{F}_q(B[n]) \), in which case we say that \( A \) and \( B \) are isokummerian. In the case of a simple variety, therefore, if \( w_{\pi_A} \) is reduced to the conjugates of \( \pi_A \), any variety \( B \) satisfying the above condition must be isogenous to a power of \( A \).

Some precise results (e.g., for product of elliptic curves) are given in [K1], and also an example due to Serre of two abelian varieties \( A \) and \( B \) over a finite field, simple and non-isogenous over \( \mathbb{F}_q \), such that \( \Phi_A = \Phi_B \). (In particular, in such a case \( w_A \) contains strictly the set of conjugates of \( \pi_A \)).

Our main result shows that for “most” abelian varieties over finite fields, \( w_A \) is the set of eigenvalues of \( \pi_A \). What “most” means has to be specified, of course, and there are actually at least two natural ways of doing this, taking \( A \) up to isomorphism or isogeny. We will consider both possibilities, using a common lemma and specialized arguments. In the isomorphism case, we use rather deep results of Mumford and Chavdarov on what “most” isomorphism classes of abelian varieties over \( \mathbb{F}_q \) look like; it is quite appealing that we use here both \( p \)-adic methods having to do with ordinarity and \( \ell \)-adic methods related to monodromy of \( \ell \)-adic sheaves. Those also allow us to derive some results for abelian varieties over number fields, although they are conditional on ordinarity assumptions. In

2000 Mathematics Subject Classification. Primary 11G10, 11G20, 11G25; Secondary 11N36.

Key words and phrases. Abelian varieties over finite fields, division fields, Weil numbers, ordinary abelian varieties, characteristic polynomial of Frobenius, isogeny classes, large sieve.
the isogeny case, the method is more elementary, based on lattice-point counting, using results of Howe and DiPippo, and the multidimensional large sieve inequality.

We now state precisely our main result. Let \( g \geq 1 \) be an integer, \( q = p^k \) with \( p \) prime and \( k \geq 1 \). We introduce the following:

- \( A_g(q) \) is the set of isomorphism classes of principally polarized abelian varieties of dimension \( g \) defined over \( F_q \);
- \( I_g(q) \subseteq A_g(q) \) is the subset of those varieties \( A \) such that any \( B \) isogenous to \( A \) with \( A \) is isogenous to a power of \( A \);
- \( \mathcal{A}_g(q) \) is the set of isogeny classes of abelian varieties of dimension \( g \) defined over \( F_q \);
- \( \mathcal{I}_g(q) \subseteq \mathcal{A}_g(q) \) is the subset of isogeny classes such that any \( B \) isogenous to \( A \) (isogenous to) a power of \( A \).

**Theorem 1.1.** Let \( g \geq 1 \) and \( q = p^k \) with \( p \) prime and \( k \geq 1 \). We have

\[
\lim_{n \to +\infty} \frac{|I_g(q^n)|}{|A_g(q^n)|} = 1
\]

and

\[
\lim_{n \to +\infty} \frac{|\mathcal{I}_g(q^n)|}{|\mathcal{A}_g(q^n)|} = 1.
\]

**Acknowledgments.** The results of Chavdarov [C] which are crucial for this paper were mentioned by N. Katz during a lecture; shortly afterward a question by U. Zannier made me realize that those results could be quite useful to study \( \Phi_A \) and \( w_A \) and improve on [K1]. I thank them both for these lucky coincidences...

2. **Determination of \( w_\pi \) in a special case**

In this section we consider only \( q \)-Weil numbers, and give a criterion for \( w_\pi \) to be reduced to the conjugates of \( \pi \). For simplicity we assume that \( \pi \) does not have real conjugates, hence \( \pi \) is of even degree \( 2g \). Let \( K_\pi \subset \mathbb{Q} \) be the Galois closure of \( \mathbb{Q}(\pi) \). For every conjugate \( \pi_i \) of \( \pi \), \( q/\pi_i \) is also a conjugate of \( \pi \); if we fix an embedding \( \mathbb{Q} \subset \mathbb{C} \), we have \( q/\pi_i = \overline{\pi}_i \), the complex conjugate of \( \pi_i \).

**Proposition 2.1.** Let \( p \) be prime, \( q = p^k \) with \( k \geq 1 \). Let \( \pi \) be a \( q \)-Weil number such that \( [\mathbb{Q}(\pi) : \mathbb{Q}] = 2g \). Let \( G \) denote the Galois group of the Galois closure \( K_\pi \) of \( \mathbb{Q}(\pi) \). Let \( (\pi_i, \overline{\pi}_i) \), \( 1 \leq i \leq g \), be the Galois conjugates of \( \pi \) in \( K_\pi \), in complex conjugate pairs. Assume that:

1. For all \( i \), \( 1 \leq i \leq g \), \( \pi_i \) and \( \overline{\pi}_i \) are coprime in \( K_\pi \).
2. For all \( i \), \( 1 \leq i \leq g \), there exists \( \sigma_i \in G \) such that \( \sigma_i(\pi_i) = \pi_i \) and \( \sigma_i(\pi_j) = \overline{\pi}_j \) for \( j \neq i \).

Then \( w_\pi \) is the set of conjugates of \( \pi \).

**Proof.** Let \( c \in G \) be the restriction of complex conjugation, so that \( c(\pi_i) = \overline{\pi}_i \) and \( c(\overline{\pi}_i) = \pi_i \) for every \( i \). Thus setting

\[
\sigma_{i,j} = c \sigma_i \sigma_j \in G
\]

we have for \( i \neq j \) the relations

\[
(2.1) \quad \sigma_{i,j}(\pi_i) = \pi_i, \quad \sigma_{i,j}(\pi_j) = \overline{\pi}_j, \quad \sigma_{i,j}(\pi_k) = \pi_k \quad \text{for} \quad k \notin \{i, j\}.
\]

Fix a prime ideal \( \mathfrak{p} \) in \( K_\pi \) dividing \( (p) \). Since \( \mathfrak{p} \mid p \mid q = \pi_1 \overline{\pi}_1 \) and \( \pi_i, \overline{\pi}_i \) are coprime by assumption, we see that \( \mathfrak{p} \) divides one and only one of \( \pi_i \) and \( \overline{\pi}_i \). We renumber/pair the
conjugates so that $p \mid \pi_i$, and $p \nmid \bar{\pi}_i$ for $1 \leq i \leq g$. Notice this doesn’t affect the existence of $\sigma_i$, $\sigma_{i,j}$ with properties as stated for the new numbering.

Let $\nu = v_p(q) \geq 1$ where $v_p$ is the valuation on $K_\pi$ associated to $p$. Notice that by coprimality again we have

\begin{equation}
\nu = v_p(q) = v_p(q) = v_p(\pi_i \bar{\pi}_i) = v_p(\pi_i) = v_p(\bar{\pi}_i).
\end{equation}

Let now $\alpha \in \Phi_\pi$ be a $q$-Weil number. We can write

\[ \alpha = q^m \prod_{1 \leq i \leq g} \pi_i^{n_i}, \]

with $n_i \in \mathbb{Z}$. We deduce from $\alpha \bar{\alpha} = q$ that

\begin{equation}
2m + n_1 + \cdots + n_g = 1,
\end{equation}

and from this we notice in particular that the sum $n_1 + \cdots + n_g$ can not be zero, in particular not all the $n_i$ can be zero.

We have $v_p(\alpha) \geq 0$, $v_p(\alpha) \geq 0$, which translate to

\[ \nu(m + n_1 + \cdots + n_g) \geq 0, \quad \nu m \geq 0. \]

Dividing by $\nu \geq 1$, summing and comparing with (2.3), we see that one of $m$ and $m + n_1 + \cdots + n_g$ is equal to 0 and the other is equal to 1.

Now we consider $\alpha \sigma_i$. This is an algebraic integer and therefore $v_p(\alpha \sigma_i) \geq 0$, $v_p(\alpha \sigma_i) \geq 0$. We have

\[ \alpha \sigma_i = q^{2m+n_1+\cdots+n_g-n_i} \pi_i^{2n_i} = q^{1-n_i} \pi_i^{2n_i}, \]

so using (2.2) these two conditions translate to

\begin{align*}
&v_p(\alpha \sigma_i) = \nu(1 + n_i) \geq 0 \\
&v_p(\alpha \sigma_i) = \nu(1 - n_i) \geq 0,
\end{align*}

which means that $n_i \in \{0, -1, 1\}$ for all $i$.

Now consider $\alpha \sigma_{i,j}$ with $i \neq j$. We have

\[ \alpha \sigma_{i,j} = q^{1-n_i-n_j} \pi_i^{2n_i} \pi_j^{2n_j}, \]

by (2.1), hence the integrality conditions $v_p(\alpha \sigma_{i,j}) \geq 0$, $v_p(\alpha \sigma_{i,j}) \geq 0$ mean

\begin{align*}
&v_p(\alpha \sigma_{i,j}) = \nu(1 + n_i + n_j) \geq 0 \\
&v_p(\alpha \sigma_{i,j}) = \nu(1 - n_i - n_j) \geq 0.
\end{align*}

The first of these shows that at most one $n_i$ can be equal to $-1$; the second that at most one $n_j$ can be equal to 1. Both of these can not occur because that would give $n_1 + \cdots + n_g = n_i + n_j = 1 - 1 = 0$, which is impossible. So either there exists exactly one $i$ with $n_i = 1$, and the other $n_j$ are 0, which gives $\alpha = \pi_i$ (because one must have $m = 0$, $m + n_1 + \cdots + n_g = 1$); or there exists exactly one $j$ with $n_j = -1$ (and the other $n_i$ are 0), which gives $\alpha = \bar{\pi}_j$ (because then $m = 1$, $m + n_1 + \cdots + n_g = 0$).

\begin{remark}
Since we actually solved the equations in terms of the parameters $(m, n_i)$ uniquely (for a given $\alpha$), we have also proved that $(q, \pi_i)$, $1 \leq i \leq q$, form a free generating set of $\Phi_\pi$ under the assumptions of the proposition. In particular, the rank of $\Phi_\pi$ is then equal to $g + 1$.
\end{remark}
**Remark 2.3.** Proposition 2.1 also applies to prove that if $A = E_1 \times \cdots \times E_k$ is a product of pairwise geometrically non-isogenous elliptic curves over a finite field $\mathbb{F}_q$ with $q$ elements, the only $q$-Weil numbers in $\Phi_A$ are the conjugates of the Frobenius elements for the $E_i$ (see [K1, Th. 3.4, (5)]). It also gives back in this case the lemma of Spiess used to prove this statement in loc. cit.

To apply Proposition 2.1 to a simple abelian variety $A/F_q$ with Frobenius $\pi_A$, we need criteria for the two conditions involved. Here we start by Condition (1), which has to do with the “behavior at $p$” (since all primes dividing $\pi$ are above $p$ in $K_\pi$) of the Frobenius of $A$.

Recall that an abelian variety $A/k$ of dimension $g$ over a field $k$ of characteristic $p$ is called ordinary if $|A[p](k)| = p^g$, which is the maximal number of $p$-torsion points there can be in characteristic $p$. If $k = \mathbb{F}_q$ is a finite field with $q$ elements, then $A$ is ordinary if and only if the middle coefficient of the characteristic polynomial of Frobenius is coprime with $q$ (see e.g. [DI1]). The following lemma is certainly well-known.

**Lemma 2.4.** Let $q = p^k$ with $p$ prime, $k \geq 1$, let $A/F_q$ be a simple ordinary abelian variety. Then for any eigenvalue $\pi$ of the Frobenius of $A$, we have $(\pi, q/\pi) = 1$ in the Galois closure of $Q(\pi)$.

**Proof.** Let $(\pi_i, q/\pi_i)$, $1 \leq i \leq g$, be the conjugates of $\pi$ with $\pi_1 = \pi$. Assume there exists $k$ and a prime ideal $p \mid p \mid q$ in $K_\pi$ dividing both $\pi_k$ and $q/\pi_k$. The middle coefficient $b$ of the characteristic polynomial of Frobenius is given by

$$b = \sum_{I,J \subseteq \{1, \ldots, g\} \mid |I| + |J| = g} \prod_{i \in I} \pi_i \prod_{j \in J} q/\pi_j.$$ 

In this sum, if $k \in I$ or $k \in J$, we have

$$p \mid \prod_{i \in I} \pi_i \prod_{j \in J} q/\pi_j$$

by assumption. Otherwise, $I$ and $J$ are both chosen inside the set $\{1, 2, \ldots, g\} \setminus \{k\}$ with $g-1$ elements, and $|I| + |J| = g$. Thus $I \cap J \neq \emptyset$. If $i \in I \cap J$, then

$$p \mid q = \pi_i \cdot q/\pi_i \mid \prod_{i \in I} \pi_i \prod_{j \in J} q/\pi_j.$$ 

Thus we find that $p$ divides all the terms in the sum giving $b$. Since $b \in \mathbb{Z}$, this means $p \mid b$. Hence $A$ is not ordinary, and the result follows by contraposition. 

This implies that any ordinary abelian variety satisfies Condition (1) of Proposition 2.1.

Note that the examples of Serre in [K1] are not ordinary (since their endomorphism rings are not commutative, which is another consequence of ordinarity, see e.g. [W] §7).

In analogy with $A_g(q), A_g(q)$, we now denote

- $A^\text{ord}_g(q) \subset A_g(q)$ the set of isomorphism classes of principally polarized ordinary abelian varieties of dimension $g$ defined over $\mathbb{F}_q$;

- $A^\text{ord}_g(q)$ the set of isogeny classes of ordinary abelian varieties of dimension $g$ defined over $\mathbb{F}_q$.

Now we come to Condition (2), where there is also a simple sufficiency criterion.

**Lemma 2.5.** Let $\pi$ be a $q$-Weil number such that $[Q(\pi) : Q] = 2g$ and such that the Galois group of $K_\pi$ over $Q$ is isomorphic to $W_{2g}$, the Weyl group of $Sp(2g)$. Then $\pi$ satisfies Condition (2) of Proposition 2.1.
Proof. Recall that $W_{2g}$ (the Galois group of a “generic” polynomial $P$ of degree $2d$ such that $X^{2d}P(1/X) = P(X)$) can be identified with the group of permutations of $g$ pairs $(2i-1, 2i)$, $1 \leq i \leq g$, such that the couples $\{2i-1, 2i\}$ are stable. In the case of the Galois group of $K_π$, the pairs can be identified with the pairs of conjugates $(π_i, q/π_i)$, which shows that $G$ can be identified with a subgroup of $W_{2g}$. If it is equal to $W_{2g}$, the existence of the required elements $σ_i$ is obvious.

\[ \square \]

**Corollary 2.6.** Let $q = p^k$ with $p$ prime and $k \geq 1$. For any simple ordinary abelian variety $A/F_q$ of dimension $g$ such that the Galois group $G$ of $K_{π_A}$ is isomorphic to $W_{2g}$, the set of $q$-Weil numbers in $Φ_A$ is equal to the set of conjugates of $π_A$.

This is immediate from Proposition 2.1, Lemma 2.4, and Lemma 2.5. Again we denote:

- $B_g(q) \subset A_g(q)$ the set of isomorphism classes of absolutely simple principally polarized abelian varieties of dimension $g$ defined over $F_q$ such that the Galois group of $K_{π_A}$ is isomorphic to $W_{2g}$;
- $B_g(q) \subset A_g(q)$ the set of isogeny classes of absolutely simple abelian varieties of dimension $g$ defined over $F_q$ such that the Galois group of $K_{π_A}$ is isomorphic to $W_{2g}$.

3. **GENERAL ABELIAN VARIETIES UP TO ISOMORPHISM**

We now apply Proposition 2.1 to “generic” isomorphism classes of abelian varieties of dimension $g$. More precisely, one has to consider (for instance) the moduli space $A_g$ of abelian varieties of dimension $g$ with a principal polarization, which is known to be irreducible of dimension $g(g+1)/2$ over $Z$.

For Condition (1) of Proposition 2.1, we use Lemma 2.4. It is known that generic abelian varieties are ordinary (see [ON]1.). Thus in $A_g$, there exists a dense Zariski open subset $U \subset A_g$ such that the polarized abelian variety parameterized by any $u \in U$ is ordinary. (See also [CL] §5 for a sketch; roughly speaking, ordinarity is an open condition, and we know that ordinary abelian varieties of any dimension exist, for instance products of ordinary elliptic curves).

**Proposition 3.1.** Let $q = p^k$ with $p$ prime, $k \geq 1$. We have

\[ \lim_{n \to +∞} \frac{|A_g^{\text{ord}}(q^n)|}{|A_g(q^n)|} = 1. \]

**Proof.** Mumford’s result gives this for the corresponding counting of isomorphism classes of principally polarized abelian varieties with some rigidifying structure; then one deduces the statement above by dividing by the number of choices for the rigidifying data, and dealing with possible extra automorphisms, as done for instance in [KS] 10.7, 11.3. \[ \square \]

**Remark 3.2.** This is much weaker than what the result of Mumford implies: since the space of abelian varieties is of dimension $g(g+1)/2$ and the space of non-ordinary abelian varieties must be of dimension $\leq g(g+1)/2 - 1$, we have for $n \geq 1$

\[ |A_g(q^n)| = q^{ng(g+1)/2} + O(q^n(g(g+1)/2 - 1)), \]

\[ |A_g^{\text{ord}}(q^n)| = |A_g(q^n)| + O(q^n(g(g+1)/2 - 1)). \]

Condition (2) is not so easy to treat. We use Lemma 2.5, and the crucial fact is that Chavdarov [C] has shown that “most” abelian varieties $A/F_q^n$ with $n \to +∞$ are simple and satisfy the assumptions of that lemma.

1 The result is attributed to Mumford [Mu], although the author confesses that he doesn’t see that statement in this paper of Mumford.
Proposition 3.3. Let \( q = p^k \) with \( p \neq 2 \) prime and \( k \geq 1 \). Then we have
\[
\lim_{n \to +\infty} \frac{|B_g(q^n)|}{|A_g(q^n)|} = 1.
\]

Proof. This follows from [C, Th. 2.1], applied to a suitably “rigidified” universal family of principally polarized abelian varieties of dimension \( g \) over \( \mathbb{F}_q \), after eliminating as before the extra factor counting the rigidifying parameters (compare again [KS, 11.3]). The monodromy groups modulo \( \ell \) involved in applying Chavdarov’s Theorem are as large as possible for \( \ell > 2 \) because (for instance), it is already the case for the families of jacobians of hyperelliptic curves considered in [KS, Th. 11.0.4], which are the same as those in [C, Ex. 2.4] (this is where characteristic \( \neq 2 \) enters). This is due to J.K. Yu (unpublished). See also below for more discussion of these examples.  

We now deduce from Proposition 3.1 and Proposition 3.3 the first main result of this paper.

Theorem 3.4. Let \( q = p^k \) with \( p \) prime and \( k \geq 1 \). For \( n \geq 1 \), let \( C_g(q^n) \) be set of isomorphism classes of principally polarized absolutely simple abelian varieties \( A/\mathbb{F}_q \) of dimension \( g \) such that \( \Phi_A \cong \mathbb{Z}^{g+1} \) and \( w_A \) is equal to the set of conjugates of \( \pi_A \). Then we have
\[
\lim_{n \to +\infty} \frac{|C_g(q^n)|}{|A_g(q^n)|} = 1.
\]

Informally: “most” abelian varieties \( A \) of dimension \( g \) over \( \mathbb{F}_q \) with \( n \) large are simple, ordinary, the group \( \Phi_A \) is isomorphic to \( \mathbb{Z}^{g+1} \) and the only \( q^n \)-Weil numbers in \( \Phi_A \) are \( \pi_A \) and its conjugates.

By the criterion stated in the introduction for two varieties to be isokummerian over a finite field, we see that this theorem is equivalent with the first part (1.1) of Theorem 1.1.

Remark 3.5. As in [C] or [KS], it would be very interesting to have a corresponding result with \( n = 1 \) and \( q = p \to +\infty \); and (as in those cases) this seems very hard.

On the other hand, introducing some analytic ideas (a bilinear form estimate for representations of \( F_\ell \)-adic sheaves and “old-fashioned” large sieve as in [C] and Section 4), it is possible to improve Proposition 3.3 in some cases (in particular, if \( g \) satisfies \( p > 2g + 1 \)) to obtain a sharper estimate
\[
|I_g(q^n)| = q^{ng(g+1)/2} + O(q^{n(g(g+1)/2 - \gamma)}(\log q^n))
\]
for \( \gamma = (10g^2 + 6g + 8)^{-1} \); see [K2, Cor. 6.4].

If one does not wish to deal with the moduli space, one can apply Chavdarov’s theorem to any algebraic family of principally polarized abelian varieties over a finite field \( \mathbb{F}_q \) for which the monodromy group mod \( \ell \) is equal to \( Sp(2g, \mathbb{Z}/\ell\mathbb{Z}) \) for almost all \( \ell \), provided one can check that ordinarity is generic in that family. The simplest example are provided by taking an algebraic family of curves and then the associated jacobian family, which has a canonical principal polarization. If one takes the universal family of curves, then the generic ordinarity is a result of Miller, who gives explicit examples of ordinary curves of every genus and characteristic, so that the result follows from the openess of ordinarity and the irreducibility of the moduli space of curves. The fact that the corresponding monodromy group is \( Sp(2g) \) follows again in characteristic \( \neq 2 \) from the examples of families of hyperelliptic curves of [C, Ex. 2.4] (see also [KS, 10.2]).

It is natural to want to give similar explicit equations of families of curves which are both generically ordinary and have monodromy \( Sp(2g) \). However note that Miller’s
families

\[
\begin{align*}
y^2 &= x^{2g+1} + tx^{9+1} + x \text{ if } p \nmid g, \\
y^2 &= x^{2g+2} + tx^{9+1} + x \text{ if } p \mid g
\end{align*}
\]

fail the monodromy test (because they fail the diophantine irreducibility test, see [KS, Lemma 10.1.15], as a simple computation shows). On the other hand, the author couldn't find references to the ordinarity for the families with large monodromy of loc. cit. For the moment, we merely state the following fairly easy result:

**Proposition 3.6.** Let \( p \geq 3 \) be a prime number, \( g \geq 2 \) an integer. Put \( \delta = 1 \) if \( p \mid g \), \( \delta = 0 \) otherwise.

1. The 2-parameter family \( T \) of smooth projective curves of genus \( g \) over \( \mathbf{F}_p \) given by compactification of the affine family

\[
T_{t,u} : y^2 = (x - u)(x^{2g+\delta} + tx^g + 1)
\]

over the open subset

\[
U = \{(t, u) \in \mathbf{A}^2 \mid u^{2g+\delta} + tu^g + 1 \neq 0\} \subset \mathbf{A}^2 / \mathbf{F}_p
\]

is generically ordinary and has geometric monodromy group modulo \( \ell \) equal to \( \text{Sp}(2g, \mathbf{F}_\ell) \) for \( \ell > 2, \ell \neq p \).

2. In particular, there exists \( k \geq 1 \) and \( t_0 \in \mathbf{F}_{p^k} \) such that the 1-parameter family \( S \) of curves of genus \( g \) over \( \mathbf{F}_{p^k} \) given by

\[
S_u : y^2 = (x - u)(x^{2g+\delta} + t_0x^g + 1)
\]

with \( u \in U_{t_0} = \{(t_0, u) \in U\} \subset \mathbf{A}^1 / \mathbf{F}_{p^k} \) is generically ordinary and has geometric monodromy group modulo \( \ell \) equal to \( \text{Sp}(2g, \mathbf{F}_\ell) \) for \( \ell > 2, \ell \neq p \).

3. If \( p \nmid g \) and \( g \) is even, one can in fact take \( t_0 = 0 \), so the family

\[
S_u : y^2 = (x - u)(x^{2g} + 1)
\]

with \( u \in U_0 = \mathbf{A}^1 - \mu_{2g} \), where \( \mu_{2g} \) is the group of 2g-roots of unity, is generically ordinary and has geometric monodromy group modulo \( \ell \) equal to \( \text{Sp}(2g, \mathbf{F}_\ell) \) for \( \ell > 2, \ell \neq p \).

**Proof.** Note that for \( u = 0 \), the family \( T \) specializes to Miller’s family, and therefore the open set of ordinarity for \( T \) is not empty, hence dense. Moreover, for any fixed \( t_0 \neq \pm 1 \), the family \( S_u = T_{u,t_0} \) is of the form

\[
y^2 = f_{t_0}(x)(x - u)
\]

with \( f_{t_0} \) a monic polynomial of degree \( 2g \) which has distinct roots in \( \overline{\mathbf{F}}_p \), as a simple computation shows. Hence it is of the form considered in [C, Ex. 2.4] and [KS, 10.1], and therefore has the required monodromy. As the monodromy groups can only become smaller by taking such a 1-parameter subfamily of \( T \), the result follows.

Now generic ordinarity for \( T \) implies that for some \( t_0 \in \mathbf{A}^1(\overline{\mathbf{F}}_p) - \{\pm 1\} \) at least the restricted subfamily \( S_u = T_{u,t_0} \) with \( u \) as parameter must contain an ordinary curve. As it still has the required monodromy groups, the existence result (2) follows.

When \( p \nmid g \), and \( t = t_0 = 0 \), Miller’s curve has equation

\[
y^2 = x^{2g+1} + x.
\]

The recipe in [MI, §2] for computing the (dual of the) Hasse-Witt matrix for this curve shows that it is invertible, hence the curve is ordinary, if for every \( u, 0 \leq u \leq g - 1 \), there
exist unique integers $r, t \geq 0$ such that
\[ r + t = \frac{p-1}{2} \]
\[ 2gt + \frac{p+1}{2} + u = p(v+1), \]
where $v$ is uniquely determined by $0 \leq v \leq g-1$ and the congruence
\[
\frac{p+1}{2} + u \equiv p(v+1) \pmod{g}.
\]
It is easy to see (following Miller’s argument) that the equations for $r$ and $t$ have at most one solution, and that this solution exists if and only if
\[ v + 1 \equiv u + \frac{p+1}{2} \pmod{2}. \]
If $g$ is even, then \[3.1\] implies this.\footnote{On the other hand, if $g$ is odd, the residue modulo 2 of this expression will take both values.}

We now come to some global consequences that follow also from other results of Chavdarov’s paper. Those have the virtue of concerning individual abelian varieties, as the exceptions become a set of primes of density 0 which does not affect (for instance) the Isogeny Theorem.

**Proposition 3.7.** Let $F/\mathbb{Q}$ be a number field. Let $g \geq 1$ be 2, 6, or an odd integer. Let $A/F$ be an abelian variety of dimension $g$ such that $\text{End}(A) = \mathbb{Z}$ and such that the set of primes of good reduction $p$ of $F$ where the reduction of $A$ modulo $p$ is ordinary is of density 1. Then for any abelian variety $B/F$, $B$ is isokummerian to $A$ if and only if $B$ is isogenous to a power of $A$.

**Proof.** By Chavdarov’s “horizontal” version of his result ([C Cor. 6.9]), the assumption of $A$ ensures that for all prime ideals $p$ in a set of primes of density 1, the reduced variety $A_p/F_p$ is ordinary, absolutely simple and its Frobenius has Galois group $W_{2g}$. By Corollary \[2.6\] it follows that $B_p$ must be isogenous to a power of $A_p$ for any such $p$. The dimension of $B$ fixes a $k \geq 1$ such that $B_p \simeq A_p^k$ for all primes in a set of density 1. Then by Faltings’s Isogeny Theorem, it follows that $B \simeq A^k$ over $F$.\]

The assumption of ordinarity at almost all places for varieties with $\text{End}(A) = \mathbb{Z}$ is widely expected to hold, but few results are known. For elliptic curves, it is quite easy, but this case of the proposition is already treated in [K1] without this assumption. Here is another situation that can be treated unconditionally (compare with Ogus’s theorem quoted in [CL Th. 6.3]):

**Proposition 3.8.** Let $A/\mathbb{Q}$ be an abelian surface over $\mathbb{Q}$ with $\text{End}(A) = \mathbb{Z}$. Then the set of primes of good ordinary reduction for $A$ is of density 1. Hence any $B/\mathbb{Q}$ is isokummerian to $A$ if and only if $B$ is isogenous to a power of $A$.

**Proof.** We use Serre’s $\ell$-adic methods [S]. Let $\ell$ be a prime and $\rho_\ell : G_\mathbb{Q} \to Sp(4, \mathbb{Q}_\ell)$ the $\ell$-adic representation associated to $A$. Serre has shown (this is already used in the proof of Chavdarov’s horizontal theorem) that the image of $\rho_\ell$ is dense. Consider the exterior square $\sigma_\ell = \wedge^2 \rho_\ell$. It is an $\ell$-adic representation of rank 6 and “weight” 1, and it is faithful, so the closure $G_\ell$ of the image of $\sigma_\ell$ is again isomorphic to $Sp(4, \mathbb{Q}_\ell)$. Moreover, for any prime $p \neq \ell$ of good reduction, the properties of $\rho_\ell$ and standard algebra show that the trace of the image by $\sigma_\ell$ of a Frobenius element $\sigma_p$ at $p$ is the middle coefficient $b_2$ of the characteristic polynomial of the Frobenius of $A$ modulo $p$.\]
Hence, by the characterization of ordinarity already stated, $A$ has ordinary reduction at $p$ if and only if this trace $\text{Tr} \sigma_\ell(\sigma_p)$ is not divisible by $p$.

However, by the Riemann Hypothesis for $A$ modulo $p$, we have

$$|\text{Tr} \sigma_\ell(\sigma_p)| \leq 6p,$$

so if $A$ is not ordinary at $p$, the trace must belong to set $\{-6p, -5p, \ldots, 0, p, \ldots, 6p\}$. Let $t$ be any of these thirteen values. We claim that the set of primes $p$ for which $\text{Tr} \sigma_\ell(\sigma_p) = t$ is of density 0. Clearly this implies the proposition.

The proof of the claim is easy: since $\det \sigma_\ell(\sigma_p) = p^4$, if $p$ satisfies the stated condition then we have

$$\sigma_p \in X_t = \{g \in G_\ell \mid (\text{Tr} g)^4 - t^4 \det g = 0\}.$$

Using $G_\ell \simeq Sp(4, Q_\ell)$ and simple computations, it is easy to see that $X_t$ is a closed subset of $G_\ell$ of Minkowski dimension $< \dim Sp(4)$ (see [S, §3] for the definition of Minkowski, or $M$-dimension). Hence by Theorem 10 of loc. cit., the set of primes with $\sigma_p \in X_t$ is of density 0. □

In a general higher dimensional situations (over $Q$, say), the non-ordinary primes are such that the trace $t$ of the $g$-th exterior power of the representation on the Tate module are divisible by $p$, which for $g \geq 3$ allows an unbounded number of values of $t$ (for $g = 3$, $\text{Tr} \wedge^3 \rho_\ell(\sigma_p) = pk$ with $|k| \leq 20\sqrt{p}$). Even using explicit forms of the Chebotarev density theorem (on GRH) to detect each value, the uniformity is not sufficient to obtain any non-trivial result.

Remark 3.9. In [K1], the question of the “splitting behavior” of a simple abelian variety $A/Q$ at all primes is also raised: is it true that the reduction modulo $p$ of $A$ remains simple for almost all $p$? In fact, the “horizontal” statements of Chavdarov already deal with this. For instance, this holds if $A/Q$ has the property that the Galois group of the field $Q(A[\ell])$ generated by the points of $\ell$-torsion of $A$ is equal to $Sp(2g, Z/\ell Z)$ for $\ell$ large.

4. General abelian varieties up to isogeny

Since Weil numbers, ordinarity, and having Galois group $W_{2g}$ are all isogeny-invariant properties of abelian varieties, it is natural to ask for analogs of the results of the previous section for isogeny classes of abelian varieties, instead of isomorphism classes. Going directly from one to the other is not easy, since finding the number of isomorphism classes in an isogeny class is a quite delicate question, typically related with class numbers (as can be seen most easily in the case of elliptic curves), see [W, §4.3].

However, we can use results of DiPippo and Howe to deal directly with isogeny classes. Note then that it is not necessary to introduce a polarization. This is rather satisfactory since not all isogeny classes contain a principally polarized one; see for instance [H, Th. 1.3]; however it is proved there (Th. 1.2) that any isogeny class of odd-dimensional abelian varieties over a finite field contains a principally polarized one.

Proposition 4.1. Let $g \geq 1$, $q = p^k$ with $p$ prime and $k \geq 1$. We have

$$\lim_{n \to +\infty} \frac{|A^{\text{ord}}(q^n)|}{|A_g(q^n)|} = 1,$$

and

$$|A_g(q^n)|, |A^{\text{ord}}_g(q^n)| \sim v_g \frac{\varphi(q^n)}{q^n} q^{ng(g+1)/4}.$$

for some constant $v_g > 0$.  

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This is proved by DiPippo and Howe in [DH] (see Theorem 1.1), in fact in a much more precise form. Note in particular that this says intuitively that the “dimension” of the space of isogeny classes of abelian varieties of dimension \( g \) is \( g(g+1)/4 \), half that of the moduli space.

**Proposition 4.2.** We have

\[
\lim_{n \to +\infty} \frac{|B_g(q^n)|}{|A_g(q^n)|} = 1.
\]

Using Lemma 4.3, this shows that the analogue of Theorem 3.4 holds for isogeny classes, and therefore that the second part (1.2) of Theorem 1.1 holds.

To prove Proposition 4.1, DiPippo and Howe identify the set of isogeny classes considered with a set of lattice points in a region \( V_{g,n} \subset \mathbb{R}^g \). We argue similarly for Proposition 4.2, except that we do not need to be so precise because we only look for an upper bound on the number of isogeny classes with “smaller” Galois group, which is a question of probabilistic Galois theory. It is straightforward to adapt here the method of Gallagher [G] based on the large sieve inequality. It has already been shown, using those methods, that self-reciprocal polynomials of degree \( 2g \) and bounded height have generically \( W_{2g} \) as Galois group (see [DDS]), but our parameter set is different.

Let \( A/\mathbb{F}_q \) be an abelian variety of dimension \( g \) over a number field. The characteristic polynomial of Frobenius \( f_A \) of \( A \) is of degree \( 2g \) with real roots of even multiplicity and complex roots arising in pairs \( (\alpha, q/\alpha) \). Therefore one can write

\[
f_A = (X^{2g} + q^g) + a_1(X^{2g-1} + q^{g-1}X) + \cdots + a_gX^g,
\]

with \( a_i \in \mathbb{Z} \). To \( A \) we associate the vector \( a = (a_1, \ldots, a_g) \in \mathbb{Z}^g \).

**Lemma 4.3.** Let \( g \geq 1 \), let \( q = p^k \) with \( p \) prime and \( k \geq 1 \). For any abelian variety \( A/\mathbb{F}_q \), the vector \( a \) above satisfies \( a \in \mathbb{Z}^g \cap R_{g,q} \) where

\[
R_{g,q} = \left\{ (x_1, \ldots, x_g) \in \mathbb{R}^g \mid |x_i| \leq \begin{pmatrix} g \end{pmatrix} q^{i/2} \right\}.
\]

**Proof.** This is obvious by the Riemann Hypothesis and the definition of \( a_i \). \( \square \)

The analytic ingredient we need is the following consequence of the large sieve inequality.

**Lemma 4.4.** Let \( g \geq 1 \). For \( 1 \leq i \leq g \), let \( X_i \geq 1 \) and let

\[
R = \left\{ (x_1, \ldots, x_g) \in \mathbb{Z}^g \mid |x_i| \leq X_i \text{ for } 1 \leq i \leq g \right\} \subset \mathbb{R}^g.
\]

Let \( y \geq 2 \) and for all primes \( p \leq y \), let \( \Omega(p) \subset (\mathbb{Z}/p\mathbb{Z})^g \) be a finite set of cardinality \( \omega(p) \). Let

\[
P(y) = \sum_{p \leq y} \omega(p)p^{-g}
\]

and for any \( a \in \mathbb{Z}^g \) let \( P(a, y) \) denote the number of \( p \leq y \) such that \( a \pmod{p} \in \Omega(p) \). Then we have

\[
\sum_{a \in R} (P(a, y) - P(y))^2 \ll P(y) \prod_{j=1}^k (X_j + y^2),
\]

the implied constant depending only on \( g \).
Proof. We derive this from the following multidimensional (trigonometric) large sieve inequality: for any finite set of vectors \( Y \subset (\mathbb{R}/\mathbb{Z})^g \) such that \( \max \| \alpha_k - \beta_k \| \geq \delta \) for two elements \( \alpha \neq \beta \) in \( Y \) (where \( \| x - y \| \) is the distance in \( \mathbb{R}/\mathbb{Z} \)), and for any complex numbers \( f(x) \) defined for \( x \in R \), we have

\[
\sum_{\alpha \in Y} \left| \sum_{x \in R} f(x)e(\langle x, \alpha \rangle) \right|^2 \ll \prod_{k=1}^{g} (X_i + \delta^{-1} \sum_{x \in R} |f(x)|^2),
\]

where the implied constant depends only on \( g \). This is a special case of [Hun Th. 1].

To obtain the lemma from this, proceed as in Lemma A of [G], which we repeat for convenience: let \( \chi_p \) be the characteristic function of \( \Omega(p) \), and expand it in Fourier series

\[ \chi_p(a) = \sum_{\alpha \in (\mathbb{Z}/p\mathbb{Z})^g} \hat{\chi}_p(\alpha)e(\langle a, \alpha \rangle/p) \] with \( \hat{\chi}_p(\alpha) = p^{-g} \sum_{a \in \Omega(p)} e(\langle -a, \alpha \rangle/p). \)

Thus we have

\[
\hat{\chi}_p(0) = p^{-g} \omega(p), \quad \sum_{\alpha \neq 0} |\hat{\chi}_p(\alpha)|^2 \leq \sum_{\alpha} |\hat{\chi}_p(\alpha)|^2 = p^{-g} \omega(p).
\]

We have for \( a \in R \)

\[
P(a, y) = \sum_{p \leq y, \alpha \in (\mathbb{Z}/p\mathbb{Z})^g} \hat{\chi}_p(\alpha)e(\langle a, \alpha \rangle/p) = P(y) + \sum_{p \leq y, \alpha \neq 0} \hat{\chi}_p(\alpha)e(\langle a, \alpha \rangle/p).
\]

Denote by \( R(a, y) \) the inner sum. We now write by Cauchy’s inequality and (4.3)

\[
\sum_{a \in R} |R(a, y)|^2 = \sum_{p \leq y} \sum_{\alpha \neq 0} \hat{\chi}_p(\alpha) \sum_{a \in R} R(a, y)e(\langle a, \alpha \rangle/p)
\]

\[
\leq \left( \sum_{p \leq y} \sum_{\alpha \neq 0} |\hat{\chi}_p(\alpha)|^2 \right)^{1/2} \left( \sum_{p \leq y} \sum_{\alpha \neq 0} \left| \sum_{a \in R} R(a, y)e(\langle a, \alpha \rangle/p) \right|^2 \right)^{1/2}
\]

\[
\leq P(y)^{1/2} \left( \sum_{p \leq y} \sum_{\alpha \neq 0} \left| \sum_{a \in R} R(a, y)e(\langle a, \alpha \rangle/p) \right|^2 \right)^{1/2}
\]

and applying the trigonometric large sieve inequality (4.2) with the trivial spacing estimate for distinct vectors \( \alpha/p, \beta/q \in (\mathbb{R}/\mathbb{Z})^g \), \( p, q \leq y \), this gives

\[
\sum_{a \in R} |R(a, y)|^2 \ll P(y)^{1/2} \left( \prod_{k=1}^{g} (X_i + y^2) \sum_{a \in R} |R(a, y)|^2 \right)^{1/2}
\]

so

\[
\sum_{a \in R} |R(a, y)|^2 \ll P(y) \prod_{k=1}^{g} (X_i + y^2).
\]

As, by (4.4), we have

\[
\sum_{a \in R} (P(a, y) - P(y))^2 = \sum_{a \in R} |R(a, y)|^2;
\]

we are done. \( \square \)

Proof of Proposition 4.2. First, for any \( g \)-tuple \( a = (a_1, \ldots, a_g) \) in a ring \( R \), we denote

\[ h_a = X^g + a_1 X^{g-1} + \cdots + a_{g-1} X + a_1 \in R[X] \]

and

\[ f_a = X^g h_a(X + X^{-1}) \in R[X]. \]
Let $A$ be an abelian variety and $f_A$ the characteristic polynomial of Frobenius for $A$ and $G$ the Galois group of its splitting field, which can be seen (in possibly many ways) as a subgroup of $W_{2g}$. By Lemma 2 of [DDS], we have $G = W_{2g} \subset G_{2g}$ if $G$ contains a 2-cycle, a 4-cycle, a $(2g-2)$-cycle and a $2g$-cycle.

For $\ell \in \{2, 4, 2g-2, 2g\}$, let $E_\ell$ denote the number of lattice points $a = (a_1, \ldots, a_g)$ in the region $R_{g,q}$ defined in Lemma 4.3 such that the polynomial $f = f_a$ is either reducible or such that the Galois group $G_a$ of the splitting field of $f$, seen as a subgroup of $W_{2g}$ again, does not contain an $\ell$-cycle. By the observation above and Lemma 4.3, it follows that the number $E$ of isogeny classes of abelian varieties $A/F_q$ with $f_A$ not having Galois group $W_{2g}$ satisfies

$$E \leq E_2 + E_4 + E_{2g-2} + E_{2g}.$$

For each $\ell$, we know from classical algebraic number theory (see e.g. [vdW, §61]) that if the polynomial $f_a$ reduces modulo some prime $p$ to a polynomial $f_a \pmod{p} \in \mathbb{F}_p[X]$ which factorizes as a product of $2g-\ell$ distinct linear factors and a single irreducible polynomial of degree $\ell$, then $G_a$ contains an $\ell$-cycle. Therefore, choosing $y \geq 2$ arbitrary and putting

$$\Omega(p) = \{a = (a_1, \ldots, a_g) \in (\mathbb{Z}/p\mathbb{Z})^g \mid f_a \pmod{p} \text{ factorizes as } 2g-\ell \text{ distinct linear factors, and one irreducible factor of degree } \ell\}$$

for $p \leq y$, we see that for $a$ such that $G_a$ does not contain an $\ell$-cycle we have $f_a \pmod{p} \notin \Omega(p)$ for all $p \leq y$. With notation as in Lemma 4.4 with $X_i = (g)_i^{q^{i/2}}$ (so $R = R_{g,q}$), we have therefore $P(a, y) = 0$, and the large sieve inequality implies by positivity that

$$E_\ell P(y)^2 \ll P(y) \prod_{1 \leq i \leq g} \left(q^{i/2} + y^2\right)$$

where the implied constant depends only on $g$. However by Lemma 3 of [DDS] (see p. 269, or compare [G, p. 96, l. 10]) we have for $y \geq 3$ the lower bound

$$P(y) = \frac{C_\ell}{|W_{2g}|} \pi(y) + O(\log \log y) \gg \pi(y),$$

where $C_\ell$ is the number of $\ell$-cycles in $W_{2g}$, where the implied constant depend only on $g$. Thus we get by the Prime Number Theorem (Chebychev’s elementary lower-bound estimate suffices) that

$$E_\ell \ll \prod_{1 \leq i \leq g} \left(q^{i/2} + y^2\right)y^{-1} \log y.$$

We choose $y^2 = q^{1/2}$, so that

$$\prod_{1 \leq i \leq g} \left(q^{i/2} + y^2\right) \leq 2^g q^{g(g+1)/4}$$

and

$$E_\ell \ll q^{g(g+1)/4 - 1/4} \log q,$$

hence

$$E \ll q^{g(g+1)/4 - 1/4} \log q$$

with an implied constant depending only on $g$. By comparison with (4.1), we see that Proposition 4.2 is proved. □
Remark 4.5. The bound obtained from the large sieve estimate may seem quite poor because of the choice of a rather small $y$, constrained by the smallest $X_i$. One may certainly expect that having a small Galois group would be of “codimension” at least 1, which would mean essentially $E \ll q^{(g+1)/4-1/2}$. There is a similar discrepancy between what is proved and what is expected in other problems of probabilistic Galois theory.

Remark 4.6. In contrast with the isomorphism case, the results above do not yield examples of “thinner” families of isogeny classes which would be ordinary and have the $W_{2g}$ as associated Galois group. Most notably, it is by no means clear how to prove the analogue of (1.2) where the isogeny classes are Jacobians of curves of genus $g$ (equivalently, where arbitrary Weil numbers are replaced by those associated with curves). Distinguishing Jacobians among abelian varieties over a finite field is a deep unsolved problem.

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