

SERRE WEIGHTS FOR MOD p HILBERT MODULAR FORMS: THE TOTALLY RAMIFIED CASE

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ABSTRACT. We study the possible weights of an irreducible 2-dimensional modular mod p representation of $\text{Gal}(\overline{F}/F)$, where F is a totally real field which is totally ramified at p . In most cases we determine the precise list of possible weights; in the remaining cases we determine the possible weights up to a short and explicit list of exceptions.

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1. INTRODUCTION

Let p be a prime number. The study of the possible weights of a mod p modular Galois representation was initiated by Serre in his famous paper [Ser87]. This proposed a concrete conjecture (“the weight part of Serre’s conjecture”) relating the weights to the restriction of the Galois representation to an inertia subgroup at p . This conjecture was resolved (at least for $p > 2$) by work of Coleman-Voloch, Edixhoven and Gross (see [Edi92]).

More recently the analogous questions for Hilbert modular forms have been a focus of much investigation, beginning with the seminal paper [BDJ08]. Let F be a totally real field with absolute Galois group G_F . Then to any irreducible modular representation

$$\bar{\rho} : G_F \rightarrow \text{GL}_2(\overline{\mathbb{F}}_p)$$

there is associated a set of weights $W(\bar{\rho})$, the set of weights in which $\bar{\rho}$ is modular (see section 2 for the definitions of weights and of what it means for $\bar{\rho}$ to be modular of a certain weight). Under the assumption that p is unramified in F the paper [BDJ08] associated to $\bar{\rho}$ a set of weights $W^2(\bar{\rho})$, and conjectured that $W^2(\bar{\rho}) = W(\bar{\rho})$. Many cases of this conjecture were proved in [Gee06b].

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The set $W^2(\bar{\rho})$ depends only on the restrictions of $\bar{\rho}$ to inertia subgroups at places dividing p . In the case that these restrictions are tamely ramified, the conjecture is completely explicit, while in the general case the set depends on some rather delicate questions involving extensions of crystalline characters.

Schein [Sch08a] has proposed a generalisation of the conjecture of [BDJ08] in the tame case, removing the restriction that p be unramified in F . Not much is currently known about this conjecture; [Sch08a] proves some results towards the implication $W(\bar{\rho}) \subset W^2(\bar{\rho})$, but very little is known about the harder converse implication in the case that p is ramified. It is clear that the techniques of [Gee06b] will not on their own extend to the general case, as they rely on combinatorial results which are false if p ramifies.

In this paper, we prove most cases of the conjecture of [Sch08a] in the case that p is totally ramified in F . Our techniques do not depend on the fact that there is only a single prime of F above p , and they would extend to the case where every prime of F above p has residue field \mathbb{F}_p (or in combination with the techniques of [Gee06b], to the case where every prime of F above p is either unramified or totally ramified). We have restricted to the case that p is totally ramified in order to simplify the exposition.

We assume throughout that p is odd, and that $\bar{\rho}|_{G_{F(\zeta_p)}}$ is irreducible. We make a mild additional assumption if $p = 5$. All of these restrictions are imposed by our use of the modularity lifting theorems of [Kis07b] (or rather, by their use in [Gee06a]). Let $(p) = \mathfrak{p}^e$ in \mathcal{O}_F , where $e = [F : \mathbb{Q}]$. Under these assumptions, we are able to prove that if $\bar{\rho}|_{G_{F_p}}$ is irreducible, then $W(\bar{\rho}) = W^2(\bar{\rho})$. If $\bar{\rho}|_{G_{F_p}}$ is a sum of two characters, then we show that $W(\bar{\rho}) \subset W^2(\bar{\rho})$, and that equality holds if $e \geq p$. If $e \leq p - 1$ then we prove that the weights in $W^2(\bar{\rho})$ all occur except that we miss between zero and four weights; under the extra hypothesis that $\bar{\rho}$ has an ordinary modular lift, we can usually (but not quite always) treat these exceptions as well.

We establish that $W(\bar{\rho}) \subset W^2(\bar{\rho})$ by a computation using Breuil modules with descent data, in the same style as analogous computations in the literature; we have to use a few tricks in boundary cases, but these arguments are more or less standard.

For the harder converse, our techniques are roughly a combination of those of [Gee06b] and an argument due to Kevin Buzzard, which uses a technique known as “weight cycling”. This argument was first written up in section 5 of [Tay06] in the case that p splits completely in F . The argument essentially depends only on the residue field of primes dividing p , and thus applies equally well in our totally ramified setting. It is the use of this argument that entails our restriction to the totally ramified case, rather than permitting arbitrary ramification. The idea of combining these two approaches is, as far as we know, completely new.

As in [Gee06b], the plan is to construct modular lifts of $\bar{\rho}$ which are potentially Barsotti-Tate of specific type, using the techniques of Khare-Wintenberger, as explained in [Gee06a]. These techniques reduce the construction of such lifts to the purely local problem of exhibiting a single potentially Barsotti-Tate lift of $\bar{\rho}|_{G_{F_p}}$ of the appropriate type. In the case that $\bar{\rho}|_{G_{F_p}}$ is irreducible, writing down such a lift is rather non-trivial; in fact, as far as we are aware, no-one has written down such a lift in any case in which $e > 1$. We accomplish this by means of an explicit construction of a corresponding strongly divisible module.

The immediate consequence of the existence of these lifts is that $\bar{\rho}$ is modular of one of two weights, the constituents of a certain principal series representation. In [Gee06b] we were able to conclude that only one of these two weights was actually possible, but in the totally ramified case $\bar{\rho}$ is frequently modular of both of these weights, so no such argument is possible. It is at this point that we employ weight cycling. Crucially, we can frequently ensure that our lift is non-ordinary, and when this holds weight cycling ensures that $\bar{\rho}$ is modular of both weights. The cases where we cannot guarantee a non-ordinary lift are certain of those for which $\bar{\rho}|_{G_{F_p}}$ is reducible and $e < p$, which is why our results are slightly weaker in this case.

We note that our methods should also be applicable in the non-tame case, and should give similar results, subject to the appropriate local calculations. For explicit conjectures in this case (“explicit” in the sense of [BDJ08], i.e., in terms of certain crystalline extensions) see the forthcoming [GS].

We now detail the outline of the paper. In section 2 we give our initial definitions and notation. In particular, we introduce spaces of algebraic modular forms on definite quaternion algebras, and we explain what it means for $\bar{\rho}$ to be modular of a specific weight. Note that we work throughout with these spaces of forms, rather than their analogues for indefinite quaternion algebras as used in [Sch08a] or [BDJ08]. While our results do not immediately go over to their setting, our proofs do; both the results on the existence of Barsotti-Tate lifts of specified type and the weight cycling argument are available in that case (for the latter, see [Sch08b]).

In section 3 we explain which tame lifts we will need to consider, and the relationship between the existence of modular lifts of specified types and the property of being modular of a certain weight. This amounts to recalling certain concrete instances of the local Langlands correspondence for GL_2 and local-global compatibility. All of this material is completely standard.

We give an exposition of the weight cycling result in section 4, adapted to the situation at hand. In particular, we combine weight cycling with the results of earlier sections to give a result establishing that $\bar{\rho}$ is modular of a particular weight provided that it has a modular lift which is potentially Barsotti-Tate lift of a particular type and is non-ordinary.

Having done this, we now need some concrete results on the existence of (local) potential Barsotti-Tate representations of particular type that lift $\bar{\rho}|_{G_{F_p}}$. We warm up for these calculations by establishing (in the tame case) the inclusion $W(\bar{\rho}) \subset W^?(\bar{\rho})$ in section 5. This uses a calculation with Breuil modules. In section 6.1 we produce the required lifts in the case that $\bar{\rho}|_{G_{F_p}}$ is reducible. This case is relatively straightforward, as we are able to use reducible lifts. The irreducible case is considerably more challenging, and is completed in sections 6.2 and 6.3, where we explicitly construct the lifts by writing down the corresponding strongly divisible modules.

Finally, in section 7 we combine these results with the lifting techniques of [Gee06a] and some combinatorial arguments to prove the main theorems.

2. NOTATION AND ASSUMPTIONS

Let p be an odd prime. Fix an algebraic closure $\bar{\mathbb{Q}}$ of \mathbb{Q} , an algebraic closure $\bar{\mathbb{Q}}_p$ of \mathbb{Q}_p , and an embedding $\bar{\mathbb{Q}} \hookrightarrow \bar{\mathbb{Q}}_p$. We will consider all finite extensions of \mathbb{Q} (respectively \mathbb{Q}_p) to be contained in $\bar{\mathbb{Q}}$ (respectively $\bar{\mathbb{Q}}_p$). If K is such an extension, we let G_K denote its absolute Galois group $\text{Gal}(\bar{K}/K)$. Let F be a totally real

field in which p is totally ramified, say $(p) = \mathfrak{p}^e$. Choose a uniformiser $\pi_{\mathfrak{p}} \in \mathfrak{p}$. Let $\bar{\rho} : G_F \rightarrow \mathrm{GL}_2(\overline{\mathbb{F}}_p)$ be a continuous Galois representation. Assume from now on that $\bar{\rho}|_{G_F(\zeta_p)}$ is absolutely irreducible. If $p = 5$ and the projective image of $\bar{\rho}$ is isomorphic to $\mathrm{PGL}_2(\mathbb{F}_5)$, assume further that $[F(\zeta_5) : F] = 4$. We normalise the isomorphisms of local class field theory so that a uniformiser corresponds to a geometric Frobenius element.

We wish to discuss the Serre weights of $\bar{\rho}$. We choose to work with totally definite quaternion algebras. We recall the basic definitions and results that we need, adapted to the particular case where F is totally ramified at p .

Let D be a quaternion algebra with center F which is ramified at all infinite places of F and at a set Σ of finite places, which does not contain \mathfrak{p} . Fix a maximal order \mathcal{O}_D of D and for each finite place $v \notin \Sigma$ fix an isomorphism $(\mathcal{O}_D)_v \xrightarrow{\sim} M_2(\mathcal{O}_{F_v})$. For any finite place v let π_v denote a uniformiser of F_v .

Let $U = \prod_v U_v \subset (D \otimes_F \mathbb{A}_F^f)^\times$ be a compact open subgroup, with each $U_v \subset (\mathcal{O}_D)_v^\times$. Furthermore, assume that $U_v = (\mathcal{O}_D)_v^\times$ for all $v \in \Sigma$.

Take A a topological \mathbb{Z}_p -algebra. Fix a continuous representation $\sigma : U_{\mathfrak{p}} \rightarrow \mathrm{Aut}(W_\sigma)$ with W_σ a finite free A -module. We regard σ as a representation of U in the obvious way (that is, we let U_v act trivially if $v \nmid p$). Fix also a character $\psi : F^\times \backslash (\mathbb{A}_F^f)^\times \rightarrow A^\times$ such that for any place v of F , $\sigma|_{U_v \cap \mathcal{O}_{F_v}^\times}$ is multiplication by ψ^{-1} . Then we can think of W_σ as a $U(\mathbb{A}_F^f)^\times$ -module by letting $(\mathbb{A}_F^f)^\times$ act via ψ^{-1} .

Let $S_{\sigma, \psi}(U, A)$ denote the set of continuous functions

$$f : D^\times \backslash (D \otimes_F \mathbb{A}_F^f)^\times \rightarrow W_\sigma$$

such that for all $g \in (D \otimes_F \mathbb{A}_F^f)^\times$ we have

$$f(gu) = \sigma(u)^{-1} f(g) \text{ for all } u \in U,$$

$$f(gz) = \psi(z) f(g) \text{ for all } z \in (\mathbb{A}_F^f)^\times.$$

We can write $(D \otimes_F \mathbb{A}_F^f)^\times = \prod_{i \in I} D^\times t_i U(\mathbb{A}_F^f)^\times$ for some finite index set I and some $t_i \in (D \otimes_F \mathbb{A}_F^f)^\times$. Then we have

$$S_{\sigma, \psi}(U, A) \xrightarrow{\sim} \bigoplus_{i \in I} W_\sigma^{(U(\mathbb{A}_F^f)^\times \cap t_i^{-1} D^\times t_i) / F^\times},$$

the isomorphism being given by the direct sum of the maps $f \mapsto f(t_i)$. From now on we make the following assumption:

$$\text{For all } t \in (D \otimes_F \mathbb{A}_F^f)^\times \text{ the group } (U(\mathbb{A}_F^f)^\times \cap t^{-1} D^\times t) / F^\times = 1.$$

One can always replace U by a subgroup (satisfying the above assumptions, and without changing $U_{\mathfrak{p}}$) for which this holds (cf. section 3.1.1 of [Kis07a]). Under this assumption $S_{\sigma, \psi}(U, A)$ is a finite projective A -module, and the functor $W_\sigma \mapsto S_{\sigma, \psi}(U, A)$ is exact in W_σ .

We now define some Hecke algebras. Let S be a set of finite places containing Σ , \mathfrak{p} , and the primes of F such that $U_v \neq (\mathcal{O}_D)_v^\times$. Let $\mathbb{T}_{S, A}^{\mathrm{univ}} = A[T_v, S_v]_{v \notin S}$ be the commutative polynomial ring in the formal variables T_v, S_v . Consider the left action of $(D \otimes_F \mathbb{A}_F^f)^\times$ on W_σ -valued functions on $(D \otimes_F \mathbb{A}_F^f)^\times$ given by $(gf)(z) = f(zg)$. Then we make $S_{\sigma, \psi}(U, A)$ a $\mathbb{T}_{S, A}^{\mathrm{univ}}$ -module by letting S_v act via the double coset $U \begin{pmatrix} \pi_v & 0 \\ 0 & \pi_v \end{pmatrix} U$ and T_v via $U \begin{pmatrix} \pi_v & 0 \\ 0 & 1 \end{pmatrix} U$. These are independent of the choices of π_v . We will write $\mathbb{T}_{\sigma, \psi}(U, A)$ or $\mathbb{T}_{\sigma, \psi}(U)$ for the image of $\mathbb{T}_{S, A}^{\mathrm{univ}}$ in $\mathrm{End} S_{\sigma, \psi}(U, A)$.

Note that if σ is trivial, then we may also define Hecke operators at \mathfrak{p} . We let $U_{\pi_{\mathfrak{p}}}$ be the Hecke operator given by the double coset $U\left(\begin{smallmatrix} \pi_{\mathfrak{p}} & 0 \\ 0 & 1 \end{smallmatrix}\right)U$ and let $V_{\pi_{\mathfrak{p}}}$ be given by $U\left(\begin{smallmatrix} 1 & 0 \\ 0 & \pi_{\mathfrak{p}} \end{smallmatrix}\right)U$. Note that these may depend on the choice of $\pi_{\mathfrak{p}}$.

Let \mathfrak{m} be a maximal ideal of $\mathbb{T}_{S,A}^{\text{univ}}$. We say that \mathfrak{m} is in the support of (σ, ψ) if $S_{\sigma, \psi}(U, A)_{\mathfrak{m}} \neq 0$. Now let \mathcal{O} be the ring of integers in $\overline{\mathbb{Q}}_p$, with residue field $\mathbb{F} = \overline{\mathbb{F}}_p$, and suppose that $A = \mathcal{O}$ in the above discussion, and that σ has open kernel. Consider a maximal ideal $\mathfrak{m} \subset \mathbb{T}_{S, \mathcal{O}}^{\text{univ}}$ which is induced by a maximal ideal of $\mathbb{T}_{\sigma, \psi}(U, \mathcal{O})$. Then there is a semisimple Galois representation $\overline{\rho}_{\mathfrak{m}} : G_F \rightarrow \text{GL}_2(\mathbb{F})$ associated to \mathfrak{m} which is characterised up to equivalence by the property that if $v \notin S$ then $\overline{\rho}_{\mathfrak{m}}|_{G_{F_v}}$ is unramified, and if Frob_v is an arithmetic Frobenius at v then the trace of $\overline{\rho}_{\mathfrak{m}}(\text{Frob}_v)$ is the image of T_v in \mathbb{F} .

We are now in a position to define what it means for a representation to be modular of some weight. Let $F_{\mathfrak{p}}$ have ring of integers $\mathcal{O}_{F_{\mathfrak{p}}}$, and let σ be an irreducible \mathbb{F} -representation of $\text{GL}_2(\mathbb{F}_p)$, so σ is isomorphic to $\sigma_{m,n} := \det^m \otimes \text{Sym}^n \mathbb{F}^2$ for some $0 \leq m < p-1$, $0 \leq n \leq p-1$. Throughout the paper we allow m, n to vary over these ranges. We also denote by σ the representation of $\text{GL}_2(\mathcal{O}_{F_{\mathfrak{p}}})$ induced by the surjection $\mathcal{O}_{F_{\mathfrak{p}}} \rightarrow \mathbb{F}_p$.

Definition 2.1. We say that $\overline{\rho}$ is modular of weight σ if for some D, S, U, ψ , and \mathfrak{m} as above, with $U_{\mathfrak{p}} = \text{GL}_2(\mathcal{O}_{F_{\mathfrak{p}}})$, we have $S_{\sigma, \psi}(U, \mathbb{F})_{\mathfrak{m}} \neq 0$ and $\overline{\rho}_{\mathfrak{m}} \cong \overline{\rho}$.

Assume from now on that $\overline{\rho}$ is modular of some weight, and fix $D, S, U, \psi, \mathfrak{m}$ as in the definition. Write $W(\overline{\rho})$ for the set of weights σ for which $\overline{\rho}$ is modular of weight σ .

One can gain information about the weights associated to a particular Galois representation by considering lifts to characteristic zero. The key is the following basic lemma.

Lemma 2.2. *Let $\psi : F^{\times} \backslash (\mathbb{A}_F)^{\times} \rightarrow \mathcal{O}^{\times}$ be a continuous character, and write $\overline{\psi}$ for the composite of ψ with the projection $\mathcal{O}^{\times} \rightarrow \mathbb{F}^{\times}$. Fix a representation σ of $U_{\mathfrak{p}}$ on a finite free \mathcal{O} -module W_{σ} , and an irreducible representation σ' of $U_{\mathfrak{p}}$ on a finite free \mathbb{F} -module $W_{\sigma'}$. Suppose that we have $\sigma|_{U_v \cap \mathcal{O}_{F_v}^{\times}} = \psi^{-1}|_{U_v \cap \mathcal{O}_{F_v}^{\times}}$ and $\sigma'|_{U_v \cap \mathcal{O}_{F_v}^{\times}} = \overline{\psi}^{-1}|_{U_v \cap \mathcal{O}_{F_v}^{\times}}$.*

Let \mathfrak{m} be a maximal ideal of $\mathbb{T}_{S, \mathcal{O}}^{\text{univ}}$.

Suppose that $W_{\sigma'}$ occurs as a $U_{\mathfrak{p}}$ -module subquotient of $W_{\overline{\sigma}} := W_{\sigma} \otimes \mathbb{F}$. If \mathfrak{m} is in the support of $(\sigma', \overline{\psi})$, then \mathfrak{m} is in the support of (σ, ψ) .

Conversely, if \mathfrak{m} is in the support of (σ, ψ) , then \mathfrak{m} is in the support of $(\sigma', \overline{\psi})$ for some irreducible $U_{\mathfrak{p}}$ -module subquotient $W_{\sigma'}$ of $W_{\overline{\sigma}}$.

Proof. The first part is proved just as in Lemma 3.1.4 of [Kis07b], and the second part follows from Proposition 1.2.3 of [AS86a]. \square

3. TAME LIFTS

We recall some group-theoretic results from section 3 of [CDT99]. First, recall the irreducible finite-dimensional representations of $\text{GL}_2(\mathbb{F}_p)$ over $\overline{\mathbb{Q}}_p$. Once one fixes an embedding $\mathbb{F}_{p^2} \hookrightarrow M_2(\mathbb{F}_p)$, any such representation is equivalent to one in the following list:

- For any character $\chi : \mathbb{F}_p^{\times} \rightarrow \overline{\mathbb{Q}}_p^{\times}$, the representation $\chi \circ \det$.

- For any $\chi : \mathbb{F}_p^\times \rightarrow \overline{\mathbb{Q}}_p^\times$, the representation $\mathrm{sp}_\chi = \mathrm{sp} \otimes (\chi \circ \det)$, where sp is the representation of $\mathrm{GL}_2(\mathbb{F}_p)$ on the space of functions $\mathbb{P}^1(\mathbb{F}_p) \rightarrow \overline{\mathbb{Q}}_p$ with average value zero.
- For any pair $\chi_1 \neq \chi_2 : \mathbb{F}_p^\times \rightarrow \overline{\mathbb{Q}}_p^\times$, the representation

$$I(\chi_1, \chi_2) = \mathrm{Ind}_{B(\mathbb{F}_p)}^{\mathrm{GL}_2(\mathbb{F}_p)} (\chi_1 \otimes \chi_2),$$

where $B(\mathbb{F}_p)$ is the Borel subgroup of upper-triangular matrices in $\mathrm{GL}_2(\mathbb{F}_p)$, and $\chi_1 \otimes \chi_2$ is the character

$$\begin{pmatrix} a & b \\ 0 & d \end{pmatrix} \mapsto \chi_1(a)\chi_2(d).$$

- For any character $\chi : \mathbb{F}_{p^2}^\times \rightarrow \overline{\mathbb{Q}}_p^\times$ with $\chi \neq \chi^p$, the cuspidal representation $\Theta(\chi)$ characterised by

$$\Theta(\chi) \otimes \mathrm{sp} \cong \mathrm{Ind}_{\mathbb{F}_{p^2}^\times}^{\mathrm{GL}_2(\mathbb{F}_p)} \chi.$$

We now recall the reductions mod p of these representations. Let $\sigma_{m,n}$ be the irreducible $\overline{\mathbb{F}}_p$ -representation $\det^m \otimes \mathrm{Sym}^n \mathbb{F}^2$, with $0 \leq m < p-1$, $0 \leq n \leq p-1$. Then we have:

Lemma 3.1. *Let L be a finite free \mathcal{O} -module with an action of $\mathrm{GL}_2(\mathbb{F}_p)$ such that $V = L \otimes_{\mathcal{O}} \overline{\mathbb{Q}}_p$ is irreducible. Let \tilde{a} denote the Teichmüller lift of a .*

- (1) *If $V \cong \chi \circ \det$ with $\chi(a) = \tilde{a}^m$, then $L \otimes_{\mathcal{O}} \mathbb{F} \cong \sigma_{m,0}$.*
- (2) *If $V \cong \mathrm{sp}_\chi$ with $\chi(a) = \tilde{a}^m$, then $L \otimes_{\mathcal{O}} \mathbb{F} \cong \sigma_{m,p-1}$.*
- (3) *If $V \cong I(\chi_1, \chi_2)$ with $\chi_i(a) = \tilde{a}^{m_i}$ for distinct $m_i \in \mathbb{Z}/(p-1)\mathbb{Z}$, then $L \otimes_{\mathcal{O}} \mathbb{F}$ has two Jordan-Hölder subquotients: $\sigma_{m_2, \{m_1 - m_2\}}$ and $\sigma_{m_1, \{m_2 - m_1\}}$ where $0 < \{m\} < p-1$ and $\{m\} \equiv m \pmod{p-1}$.*
- (4) *If $V \cong \Theta(\chi)$ with $\chi(c) = \tilde{c}^{i+(p+1)j}$ where $1 \leq i \leq p$ and $j \in \mathbb{Z}/(p-1)\mathbb{Z}$, then $L \otimes_{\mathcal{O}} \mathbb{F}$ has two Jordan-Hölder subquotients: $\sigma_{1+j, i-2}$ and $\sigma_{i+j, p-1-i}$. Both occur unless $i = p$ (when only the first occurs), or $i = 1$ (when only the second one occurs), and in either of these cases $L \otimes_{\mathcal{O}} \mathbb{F} \cong \sigma_{1+j, p-2}$.*

Proof. This is Lemma 3.1.1 of [CDT99]. \square

In what follows, we will sometimes consider the above representations as representations of $\mathrm{GL}_2(\mathcal{O}_{F_p})$ via the natural projection map.

We now recall some definitions relating to potentially semistable lifts of particular type. We use the conventions of [Sav05].

Definition 3.2. Let τ be an inertial type. We say that a lift ρ of $\bar{\rho}|_{G_{F_p}}$ is potentially Barsotti-Tate (respectively potentially semistable) of type τ if ρ is potentially Barsotti-Tate (respectively potentially semistable with all Hodge-Tate weights equal to 0 or 1), has determinant a finite order character of order prime to p times the cyclotomic character, and the corresponding Weil-Deligne representation, when restricted to I_{F_p} , is isomorphic to τ .

Note that (at least in the potentially semistable case) this terminology is not standard, but it will be convenient in this paper.

Definition 3.3. We say that a representation $\rho : G_{F_p} \rightarrow \mathrm{GL}_2(\overline{\mathbb{Q}}_p)$ is ordinary if $\rho|_{I_{F_p}}$ is an extension of a finite order character by a finite order character times the

cyclotomic character. We say that a representation $\rho : G_F \rightarrow \mathrm{GL}_2(\overline{\mathbb{Q}}_p)$ is ordinary if $\rho|_{G_{F_p}}$ is ordinary.

We now need some special cases of the inertial local Langlands correspondence of Henniart (see the appendix to [BM02]). If $\chi_1 \neq \chi_2 : \mathbb{F}_p^\times \rightarrow \mathcal{O}^\times$, let τ_{χ_1, χ_2} be the inertial type $\chi_1 \oplus \chi_2$ (considered as a representation of I_{F_p} via local class field theory). Then we let $\sigma(\tau_{\chi_1, \chi_2})$ be a representation on a finite \mathcal{O} -module given by taking a lattice in $I(\chi_1, \chi_2)$. If $\chi : \mathbb{F}_p^\times \rightarrow \mathcal{O}^\times$, we let $\tau_\chi = \chi \oplus \chi$, and $\sigma(\tau_\chi)$ be $\chi \circ \det$.

If $\chi : \mathbb{F}_{p^2}^\times \rightarrow \mathcal{O}^\times$ with $\chi \neq \chi^p$, we let $\tau_{\chi, \chi^p} = \chi \oplus \chi^p$ (again, regarded as a representation of I_{F_p} via local class field theory), and we let $\sigma(\tau_{\chi, \chi^p})$ be a representation on a finite \mathcal{O} -module given by taking a lattice in $\Theta(\chi)$.

The following result then follows from Lemma 2.2, the Jacquet-Langlands correspondence, the precise form of the local Langlands correspondence for tame representations (*cf.* Lemma 4.2.4 of [CDT99]), and the compatibility of the local and global Langlands correspondences at places dividing p (see [Kis08]). (See the beginning of section 5 for the definition of the fundamental character ω .)

Lemma 3.4. *Fix a type τ as above (i.e., $\tau = \tau_{\chi_1, \chi_2}$, τ_χ , or τ_{χ, χ^p}). Suppose that $\bar{\rho}$ is modular of weight σ , and that σ is a $\mathrm{GL}_2(\mathbb{F}_p)$ -module subquotient of $\sigma(\tau) \otimes_{\mathcal{O}} \mathbb{F}$. Then $\bar{\rho}$ lifts to a modular Galois representation which is potentially Barsotti-Tate of type τ at \mathfrak{p} . Similarly, if $\bar{\rho}$ is modular of weight $\sigma_{m, p-1}$, then $\bar{\rho}$ lifts to a modular Galois representation which is potentially semistable of type $\tilde{\omega}^m \oplus \tilde{\omega}^m$. Conversely, if $\bar{\rho}$ lifts to a modular Galois representation which is potentially Barsotti-Tate of type τ at \mathfrak{p} , then $\bar{\rho}$ is modular of weight σ for some $\mathrm{GL}_2(\mathbb{F}_p)$ -module subquotient σ of $\sigma(\tau) \otimes_{\mathcal{O}} \mathbb{F}$.*

4. WEIGHT CYCLING

We now explain the weight cycling argument due to Kevin Buzzard which proves modularity in an additional weight in the non-ordinary case. There is an exposition of this argument in section 5 of [Tay06] in the case that p splits completely in F , and the argument goes over essentially unchanged in our setting. Since our notation and assumptions differ from those of [Tay06], we give a proof here.

Suppose that A is a field and that σ^\vee denotes the dual of σ . Then (*cf.* the discussion on page 742 of [Tay06], recalling that by assumption we have $(U(\mathbb{A}_F^f)^\times \cap t^{-1}D^\times t)/F^\times = 1$ for all $t \in (D \otimes_F \mathbb{A}_F^f)^\times$) there is a perfect pairing

$$\langle \cdot, \cdot \rangle : S_{\sigma, \psi}(U, A) \times S_{\sigma^\vee, \psi^{-1}}(U, A) \rightarrow A$$

given by

$$\langle f_1, f_2 \rangle = \sum_i \langle f_1(t_i), f_2(t_i) \rangle$$

where

$$(D \otimes_F \mathbb{A}_F^f)^\times = \prod_i D^\times t_i U(\mathbb{A}_F^f)^\times$$

and the pairing between $f_1(t_i)$ and $f_2(t_i)$ is the usual pairing between a representation and its dual. A standard calculation shows that under this pairing the adjoint of S_x is S_x^{-1} , the adjoint of T_x is $T_x S_x^{-1}$, and when it is defined the adjoint of U_{π_p} is $V_{\pi_p} S_p^{-1}$.

Let

$$U_0 = \prod_{v \nmid p} U_v \times I_{\mathfrak{p}}$$

where $I_{\mathfrak{p}}$ is the Iwahori subgroup of $\mathrm{GL}_2(\mathcal{O}_{F_{\mathfrak{p}}})$ consisting of matrices which are upper-triangular modulo \mathfrak{p} , and let

$$U_1 = \prod_{v \nmid p} U_v \times I_{\mathfrak{p}}^1$$

where $I_{\mathfrak{p}}^1$ is the subgroup of $I_{\mathfrak{p}}$ whose entries are congruent to $\begin{pmatrix} * & * \\ 0 & 1 \end{pmatrix}$ modulo \mathfrak{p} . Let $\sigma = 1$, the trivial representation, so that the operators $U_{\pi_{\mathfrak{p}}}$ and $V_{\pi_{\mathfrak{p}}}$ are defined on $S_{1,\psi}(U_1, A)$ and $S_{1,\psi^{-1}}(U_1, A)$ for any \mathcal{O} -algebra A . Let

$$\delta^n : \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} \mapsto d^n,$$

an \mathbb{F}^\times -character of the standard Borel subgroup $B(\mathbb{F}_p)$ of $\mathrm{GL}_2(\mathbb{F}_p)$. Then there is a natural embedding

$$S_{\delta^n, \psi}(U_0, \mathbb{F}) \hookrightarrow S_{1, \psi}(U_1, \mathbb{F})$$

which is equivariant for the actions of $\mathbb{T}_{S, \mathbb{F}}^{\mathrm{univ}}$, and the image of $S_{\delta^n, \psi}(U_0, \mathbb{F})$ is stable under the actions of $U_{\pi_{\mathfrak{p}}}$ and $V_{\pi_{\mathfrak{p}}}$. We use this action as the definition of $U_{\pi_{\mathfrak{p}}}$ and $V_{\pi_{\mathfrak{p}}}$ on $S_{\delta^n, \psi}(U_0, \mathbb{F})$.

There is also a natural isomorphism

$$S_{\delta^n, \psi}(U_0, \mathbb{F}) \cong S_{\mathrm{Ind}(\delta^n), \psi}(U, \mathbb{F})$$

where $\mathrm{Ind}(\delta^n)$ is obtained as the induction from $B(\mathbb{F}_p)$ to $\mathrm{GL}_2(\mathbb{F}_p)$ of δ^n . We can think of this induction as being the functions

$$\theta : \mathrm{GL}_2(\mathbb{F}_p) \rightarrow \mathbb{F}$$

with the property that for all $b \in B(\mathbb{F}_p)$, $g \in \mathrm{GL}_2(\mathbb{F}_p)$,

$$\theta(bg) = \delta^n(b)\theta(g).$$

The action of $\mathrm{GL}_2(\mathbb{F}_p)$ is by

$$(g\theta)(x) = \theta(xg).$$

This isomorphism identifies $f \in S_{\delta^n, \psi}(U_0, \mathbb{F})$ with $F \in S_{\mathrm{Ind}(\delta^n), \psi}(U, \mathbb{F})$ where

$$f(x) = F(x)(1)$$

and

$$F(x)(g) = f(xg^{-1}).$$

Now, we have a short exact sequence

$$0 \rightarrow \sigma_{0,n} \rightarrow \mathrm{Ind}(\delta^n) \rightarrow \sigma_{n,p-1-n} \rightarrow 0$$

of $\mathrm{GL}_2(\mathbb{F}_p)$ -modules and thus a short exact sequence

$$0 \rightarrow S_{\sigma_{0,n}, \psi}(U, \mathbb{F}) \xrightarrow{\alpha} S_{\mathrm{Ind}(\delta^n), \psi}(U, \mathbb{F}) \xrightarrow{\beta} S_{\sigma_{n,p-1-n}, \psi}(U, \mathbb{F}) \rightarrow 0$$

and, localising at \mathfrak{m} , a short exact sequence

$$0 \rightarrow S_{\sigma_{0,n}, \psi}(U, \mathbb{F})_{\mathfrak{m}} \xrightarrow{\alpha} S_{\mathrm{Ind}(\delta^n), \psi}(U, \mathbb{F})_{\mathfrak{m}} \xrightarrow{\beta} S_{\sigma_{n,p-1-n}, \psi}(U, \mathbb{F})_{\mathfrak{m}} \rightarrow 0.$$

Proposition 4.1. *If $n < p - 1$ and $S_{\sigma_{0,n}, \psi}(U, \mathbb{F})_{\mathfrak{m}} = 0$ then the map $V_{\pi_{\mathfrak{p}}} : S_{\mathrm{Ind}(\delta^n), \psi}(U, \mathbb{F})_{\mathfrak{m}} \rightarrow S_{\mathrm{Ind}(\delta^n), \psi}(U, \mathbb{F})_{\mathfrak{m}}$ is an isomorphism.*

Proof. Under the assumption that $S_{\sigma_{0,n},\psi}(U, \mathbb{F})_{\mathfrak{m}} = 0$, we have an isomorphism

$$S_{\text{Ind}(\delta^n),\psi}(U, \mathbb{F})_{\mathfrak{m}} \xrightarrow{\beta} S_{\sigma_{n,p-1-n},\psi}(U, \mathbb{F})_{\mathfrak{m}}.$$

We claim that there is an injection

$$\kappa : S_{\sigma_{n,p-1-n},\psi}(U, \mathbb{F})_{\mathfrak{m}} \rightarrow S_{\text{Ind}(\delta^n),\psi}(U, \mathbb{F})_{\mathfrak{m}}$$

such that $\kappa \circ \beta = V_{\pi_{\mathfrak{p}}}$. This would clearly establish the result. Of course, it is enough to construct an injection

$$\kappa : S_{\sigma_{n,p-1-n},\psi}(U, \mathbb{F}) \rightarrow S_{\text{Ind}(\delta^n),\psi}(U, \mathbb{F})$$

which commutes with the action of $\mathbb{T}_{S,\mathbb{F}}^{\text{univ}}$, and satisfies $\kappa \circ \beta = V_{\pi_{\mathfrak{p}}}$.

As explained above, we identify $S_{\text{Ind}(\delta^n),\psi}(U, \mathbb{F})$ with $S_{\delta^n,\psi}(U_0, \mathbb{F})$. First, note that (cf. the proof of Lemma 5.1 of [Tay06] or Theorem 3.4(a) of [AS86b]) the map

$$\beta : S_{\delta^n,\psi}(U_0, \mathbb{F}) \rightarrow S_{\sigma_{n,p-1-n},\psi}(U, \mathbb{F})$$

is given by

$$\beta(f)(g) = \sum_{(s:t) \in \mathbb{P}^1(\mathbb{F}_p)} f(g \cdot u(s,t)^{-1})(tX - sY)^{p-1-n}.$$

Here we are regarding elements of $\sigma_{n,p-1-n}$ as homogeneous polynomials of degree $p-1-n$ in variables X, Y in the usual way, and $u(s,t) \in \text{GL}_2(\mathcal{O}_{F_p})$ is any matrix congruent to

$$\begin{pmatrix} * & * \\ s & t \end{pmatrix}$$

modulo \mathfrak{p} .

Then the map

$$\kappa : S_{\sigma_{n,p-1-n},\psi}(U, \mathbb{F}) \rightarrow S_{\delta^n,\psi}(U_0, \mathbb{F})$$

is defined by

$$\kappa(f)(g) = f(g\gamma)(1, 0)$$

where

$$\gamma = \begin{pmatrix} 1 & 0 \\ 0 & \pi_{\mathfrak{p}} \end{pmatrix} \in \text{GL}_2(F_{\mathfrak{p}}).$$

It is easy to check that this is well-defined and equivariant for the action of $\mathbb{T}_{S,\mathbb{F}}^{\text{univ}}$, and it is obviously injective. It remains to check that $\kappa \circ \beta = V_{\pi_{\mathfrak{p}}}$.

For each $s \in \mathbb{F}_p$ we let \tilde{s} denote a lift of s to \mathcal{O}_{F_p} . Then we have the familiar decomposition

$$U_0 \begin{pmatrix} 1 & 0 \\ 0 & \pi_{\mathfrak{p}} \end{pmatrix} U_0 = \prod_{s \in \mathbb{F}_p} \begin{pmatrix} 1 & 0 \\ \tilde{s}\pi_{\mathfrak{p}} & \pi_{\mathfrak{p}} \end{pmatrix} U_0,$$

and we can take

$$u(s, 1) = \begin{pmatrix} 1 & 0 \\ \tilde{s} & 1 \end{pmatrix}.$$

Then we have

$$\begin{aligned}
(\kappa \circ \beta)(f)(g) &= (\beta f)(g\gamma)(1, 0) \\
&= \sum_{(s:t) \in \mathbb{P}^1(\mathbb{F}_p)} f(g\gamma \cdot u(s, t)^{-1}) t^{p-1-n} \\
&= \sum_{s \in \mathbb{F}_p} f(g\gamma \cdot u(s, 1)^{-1}) \\
&= \sum_{s \in \mathbb{F}_p} f\left(g \begin{pmatrix} 1 & 0 \\ \tilde{s}\pi_{\mathfrak{p}} & \pi_{\mathfrak{p}} \end{pmatrix}\right) \\
&= (V_{\pi_{\mathfrak{p}}} f)(g).
\end{aligned}$$

□

Proposition 4.2. *If $S_{\sigma_{0,p-1},\psi}(U, \mathbb{F})_{\mathfrak{m}} = 0$ then the map $U_{\pi_{\mathfrak{p}}} : S_{\sigma_{0,0},\psi}(U, \mathbb{F})_{\mathfrak{m}} \rightarrow S_{\sigma_{0,0},\psi}(U, \mathbb{F})_{\mathfrak{m}}$ is an isomorphism.*

Proof. Under the assumption that $S_{\sigma_{0,p-1},\psi}(U, \mathbb{F})_{\mathfrak{m}} = 0$, we have an isomorphism

$$S_{\text{Ind}(1),\psi}(U, \mathbb{F})_{\mathfrak{m}} \xrightarrow{\beta} S_{\sigma_{0,0},\psi}(U, \mathbb{F}).$$

We claim that there is an injection

$$\kappa : S_{\sigma_{0,0},\psi}(U, \mathbb{F}) \rightarrow S_{\text{Ind}(1),\psi}(U, \mathbb{F})$$

which commutes with the action of $\mathbb{T}_{S, \mathbb{F}}^{\text{univ}}$, and satisfies $\beta \circ \kappa = U_{\pi_{\mathfrak{p}}}$.

As above, we identify $S_{\text{Ind}(1),\psi}(U, \mathbb{F})$ with $S_{1,\psi}(U_0, \mathbb{F})$. Again, the map

$$\beta : S_{1,\psi}(U_0, \mathbb{F}) \rightarrow S_{\sigma_{0,0},\psi}(U, \mathbb{F})$$

is given by

$$\beta(f)(g) = \sum_{(s:t) \in \mathbb{P}^1(\mathbb{F}_p)} f(g \cdot u(s, t)^{-1}).$$

Then the map

$$\kappa : S_{\sigma_{0,0},\psi}(U, \mathbb{F}) \rightarrow S_{1,\psi}(U_0, \mathbb{F})$$

is defined by

$$\kappa(f)(g) = f(g\gamma)$$

where

$$\gamma = \begin{pmatrix} 1 & 0 \\ 0 & \pi_{\mathfrak{p}} \end{pmatrix} \in \text{GL}_2(\mathbb{F}_{\mathfrak{p}}).$$

It is easy to check that this is well-defined, equivariant for the action of $\mathbb{T}_{S, \mathbb{F}}^{\text{univ}}$, and it is obviously injective. It remains to check that $\kappa \circ \beta = U_{\pi_{\mathfrak{p}}}$.

Again, we may take

$$u(s, 1) = \begin{pmatrix} 1 & 0 \\ \tilde{s} & 1 \end{pmatrix},$$

and we take

$$u(1, 0) = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

Recall that we have the standard decomposition

$$U_0 \begin{pmatrix} \pi_{\mathfrak{p}} & 0 \\ 0 & 1 \end{pmatrix} U_0 = \prod_{s \in \mathbb{F}_p} \begin{pmatrix} \pi_{\mathfrak{p}} & \tilde{s} \\ 0 & 1 \end{pmatrix} U_0 \prod_{s \in \mathbb{F}_p} \begin{pmatrix} 1 & 0 \\ 0 & \mathfrak{p} \end{pmatrix} U_0.$$

Note that we have

$$\begin{pmatrix} \pi_{\mathfrak{p}} & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & \pi_{\mathfrak{p}} \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix},$$

and if $s \neq 0$ then writing $t = s^{-1}$ we have

$$\begin{pmatrix} \pi_{\mathfrak{p}} & \tilde{s} \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \tilde{t} & \pi_{\mathfrak{p}} \end{pmatrix} \begin{pmatrix} \pi_{\mathfrak{p}} & \tilde{s} \\ -\tilde{t} & (1 - \tilde{s}\tilde{t})/\pi_{\mathfrak{p}} \end{pmatrix}.$$

Then we have

$$\begin{aligned} (\beta \circ \kappa)(f)(g) &= \sum_{(s:t) \in \mathbb{P}^1(\mathbb{F}_p)} f(g \cdot u(s,t)^{-1}\gamma) \\ &= \sum_{s \in \mathbb{F}_p} f\left(g \begin{pmatrix} 1 & 0 \\ \tilde{s} & \pi_{\mathfrak{p}} \end{pmatrix}\right) + f\left(g \begin{pmatrix} 0 & \pi_{\mathfrak{p}} \\ 1 & 0 \end{pmatrix}\right) \\ &= (U_{\pi_{\mathfrak{p}}} f)(g). \end{aligned}$$

□

Now, there is a maximal ideal \mathfrak{m}^* of $\mathbb{T}_{S, \mathbb{F}}^{\text{univ}}$ with the property that for each $x \notin S$, $T_x - \alpha \in \mathfrak{m}$ if and only if $T_x S_x^{-1} - \alpha \in \mathfrak{m}^*$, and $S_x - \beta \in \mathfrak{m}$ if and only if $S_x^{-1} - \beta \in \mathfrak{m}^*$. Thus

$$\bar{\rho}_{\mathfrak{m}^\vee} \cong \bar{\rho}_{\mathfrak{m}^*}^\vee(1).$$

Then from the duality explained above between $S_{\sigma, \psi}$ and $S_{\sigma^\vee, \psi^{-1}}$, we obtain

Corollary 4.3. *If $n < p - 1$ and $S_{\sigma_{0,n}, \psi}(U, \mathbb{F})_{\mathfrak{m}} = 0$ then the map*

$$U_{\pi_{\mathfrak{p}}} : S_{\text{Ind}(\delta^{-n}), \psi^{-1}}(U, \mathbb{F})_{\mathfrak{m}}^* \rightarrow S_{\text{Ind}(\delta^{-n}), \psi^{-1}}(U, \mathbb{F})_{\mathfrak{m}}^*$$

is an isomorphism.

Proof. This follows at once from Proposition 4.1. □

Proposition 4.4. *Suppose that $0 \leq n \leq p - 1$. If $\bar{\rho}$ has a lift to a modular representation $\rho : G_F \rightarrow \text{GL}_2(\overline{\mathbb{Q}}_p)$ which is potentially Barsotti-Tate of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$ and is not ordinary, then $\bar{\rho}$ is modular of weight $\sigma_{m,n}$ and of weight $\sigma_{m+n, p-1-n}$.*

Proof. We know from Lemma 3.4 that $\bar{\rho}$ is modular of weight at least one of $\sigma_{m+n, p-1-n}$ and $\sigma_{m,n}$. Suppose for the sake of contradiction (and without loss of generality) that $\bar{\rho}$ is modular of weight $\sigma_{m+n, p-1-n}$ but not weight $\sigma_{m,n}$. Twisting, we may without loss of generality assume that $m = 0$.

Take D, S, U, ψ and \mathfrak{m} as in section 2, chosen so that if $n \neq 0$ there is an eigenform in $S_{\text{Ind}(\delta^n), \psi}(U, \overline{\mathbb{Q}}_p)$ corresponding to ρ , and if $n = 0$ there is such a form in $S_{1, \psi}(U, \overline{\mathbb{Q}}_p)$. Note that by local-global compatibility and standard properties of the local Langlands correspondence, the assumption that ρ is not ordinary shows that $U_{\mathfrak{p}}$ has a non-unit eigenvalue on $S_{\text{Ind}(\delta^n), \psi}(U, \overline{\mathbb{Q}}_p)$ (respectively $S_{1, \psi}(U, \overline{\mathbb{Q}}_p)$).

Suppose first that $n = p - 1$. Then by Proposition 4.2, $U_{\pi_{\mathfrak{p}}}$ is an isomorphism on $S_{1, \psi}(U, \mathbb{F})$; but this is a contradiction.

Suppose now that $n < p - 1$. Then by Corollary 4.3, $U_{\pi_{\mathfrak{p}}}$ is an isomorphism on $S_{\text{Ind}(\delta^{-n}), \psi^{-1}}(U, \mathbb{F})_{\mathfrak{m}}^*$. Again, this is a contradiction, as by the above duality there is an eigenform in $S_{\text{Ind}(\delta^{-n}), \psi^{-1}}(U, \overline{\mathbb{Q}}_p)_{\mathfrak{m}}^*$ corresponding to the representation $\rho^\vee(1)$. □

5. NECESSARY CONDITIONS

Suppose that K is a finite extension of \mathbb{Q}_p , with residue field k . Let $S_k = \{\tau : k \hookrightarrow \overline{\mathbb{F}}_p\}$. For each $\tau \in S_k$ we define the fundamental character $\omega_{K,\tau}$ corresponding to τ to be the composite

$$I_K \xrightarrow{\sim} \mathcal{O}_K^\times \longrightarrow k^\times \xrightarrow{\tau} \overline{\mathbb{F}}_p^\times,$$

where the first map is the isomorphism given by local class field theory, normalised so that a uniformiser corresponds to geometric Frobenius. We will generally suppress the subscript K and write simply ω_τ . If χ is a character of G_K or I_K , we denote its reduction mod p by $\overline{\chi}$.

If K is totally ramified (e.g. if $K = F_p$), we let ω be the unique fundamental character. Note that $\omega^{e(K/\mathbb{Q}_p)}$ is the (restriction to I_K of the) mod p cyclotomic character, e.g. by Lemma 6.2 below. Let σ_1, σ_2 denote the two embeddings of the quadratic extension of k into $\overline{\mathbb{F}}_p$, and let $\omega_{\sigma_1}, \omega_{\sigma_2}$ denote the two corresponding fundamental characters of I_K .

If $\overline{\rho}|_{G_{F_p}}$ is semisimple, then we define a set of predicted weights for $\overline{\rho}$ as follows.

Definition 5.1. The set $W^?(\overline{\rho})$ is the set of weights $\sigma_{m,n}$ such that there exists $1 \leq x \leq e$ with either $\overline{\rho}|_{I_{F_p}} \cong \omega_{\sigma_1}^{m+n+x} \omega_{\sigma_2}^{m+e-x} \oplus \omega_{\sigma_1}^{m+e-x} \omega_{\sigma_2}^{m+n+x}$ or $\overline{\rho}|_{I_{F_p}} \cong \omega^{m+n+x} \oplus \omega^{m+e-x}$.

Let $W(\overline{\rho})$ be the set of weights σ such that $\overline{\rho}$ is modular of weight σ . Our aim in this section is to prove that $W(\overline{\rho}) \subset W^?(\overline{\rho})$.

5.1. Breuil modules with descent data. Let k be a finite extension of \mathbb{F}_p , let $K_0 = W(k)[1/p]$, and let K be a finite Galois totally tamely ramified extension of K_0 , of degree e' . Assume that there is a uniformiser π of \mathcal{O}_K such that $\pi^{e'} \in L$, where L is a subfield of K_0 , and fix such a π . Since K/L is tamely ramified, the category of Breuil modules with coefficients and descent data is easy to describe (see [Sav06]). Let k_E be a finite extension of \mathbb{F}_p . The category $\text{BrMod}_{\text{dd},L}$ consists of quadruples $(\mathcal{M}, \text{Fil}^1 \mathcal{M}, \phi_1, \{\widehat{g}\})$ where:

- \mathcal{M} is a finitely generated $(k \otimes_{\mathbb{F}_p} k_E)[u]/u^{e'p}$ -module, free over $k[u]/u^{e'p}$.
- $\text{Fil}^1 \mathcal{M}$ is a $(k \otimes_{\mathbb{F}_p} k_E)[u]/u^{e'p}$ -submodule of \mathcal{M} containing $u^{e'} \mathcal{M}$.
- $\phi_1 : \text{Fil}^1 \mathcal{M} \rightarrow \mathcal{M}$ is k_E -linear and ϕ -semilinear (where $\phi : k[u]/u^{e'p} \rightarrow k[u]/u^{e'p}$ is the p -th power map) with image generating \mathcal{M} as a $(k \otimes_{\mathbb{F}_p} k_E)[u]/u^{e'p}$ -module.
- $\widehat{g} : \mathcal{M} \rightarrow \mathcal{M}$ are additive bijections for each $g \in \text{Gal}(K/L)$, preserving $\text{Fil}^1 \mathcal{M}$, commuting with the ϕ -, and k_E -actions, and satisfying $\widehat{g}_1 \circ \widehat{g}_2 = \widehat{g_1 \circ g_2}$ for all $g_1, g_2 \in \text{Gal}(K/L)$, and $\widehat{1}$ is the identity. Furthermore, if $a \in k \otimes_{\mathbb{F}_p} k_E$, $m \in \mathcal{M}$ then $g(au^i m) = g(a)((g(\pi)/\pi)^i \otimes 1)u^i g(m)$.

The category $\text{BrMod}_{\text{dd},L}$ is equivalent to the category of finite flat group schemes over \mathcal{O}_K together with a k_E -action and descent data on the generic fibre from K to L (this equivalence depends on π).

We choose in this paper to adopt the conventions of [BM02] and [Sav05], rather than those of [BCDT01]; thus rather than working with the usual contravariant equivalence of categories, we work with a covariant version of it, so that our formulae for generic fibres will differ by duality and a twist from those following the conventions of [BCDT01]. To be precise, we obtain the associated G_L -representation

(which we will refer to as the generic fibre) of an object of $\text{BrMod}_{\text{dd},L}$ via the functor $T_{\text{st},2}^L$.

Let E be a finite extension of \mathbb{Q}_p with integers \mathcal{O}_E , maximal ideal \mathfrak{m}_E , and residue field k_E . Recall from [Sav05, Sec. 2] that the functor $D_{\text{st},2}^K$ is an equivalence of categories between the category of E -representations of G_L which are semistable when restricted to G_K and have Hodge-Tate weights in $\{0, 1\}$, and the category of weakly admissible filtered (ϕ, N) -modules D with descent data and E -coefficients such that $\text{Fil}^0(K \otimes_{K_0} D) = K \otimes_{K_0} D$ and $\text{Fil}^2(K \otimes_{K_0} D) = 0$.

Suppose that ρ is a representation in the source of $D_{\text{st},2}^K$. Write $S = S_{K, \mathcal{O}_E}$ (notation and terminology in this paragraph are as in [Sav05, Sec. 4]). Then $T_{\text{st},2}^L$ is an equivalence of categories between strongly divisible modules \mathcal{M} (with \mathcal{O}_E -coefficients and descent data) in $S \otimes_{W(k)} D_{\text{st},2}^K(\rho)$ and Galois-stable \mathcal{O}_E -lattices in ρ ; and this equivalence is compatible with reduction mod \mathfrak{m}_E , so that applying $T_{\text{st},2}^L$ to the object $\mathcal{M}/\mathfrak{m}_E \mathcal{M}$ of $\text{BrMod}_{\text{dd},L}$ yields a reduction mod p of ρ (see [Sav05, Cor. 4.12, Prop 4.13]).

Let ℓ denote the residue field of L .

Lemma 5.2. *Let $\bar{\chi} : \text{Gal}(K/L) \rightarrow k_E^\times$ be a character, and for $c \in (\ell \otimes_{\mathbb{F}_p} k_E)^\times$ let $\mathcal{M}(\bar{\chi}, c)$ denote the rank one Breuil module with k_E -coefficients and descent data from K to L with generator v and*

$$\text{Fil}^1 \mathcal{M}(\bar{\chi}, c) = \mathcal{M}(\bar{\chi}, c), \quad \phi_1(v) = cv, \quad \hat{g}(v) = (1 \otimes \bar{\chi}(g))v$$

for $g \in \text{Gal}(K/L)$. Then $T_{\text{st},2}^L(\mathcal{M}(\bar{\chi}, 1)) = \bar{\chi}$, and $T_{\text{st},2}^L(\mathcal{M}(\bar{\chi}, c))$ is an unramified twist of $\bar{\chi}$.

Proof. Let $\chi : \text{Gal}(K/L) \rightarrow E^\times$ be the Teichmüller lift of $\bar{\chi}$. For $\tilde{c} \in (W(\ell) \otimes \mathcal{O}_E)^\times$ lifting c , define a weakly admissible filtered (ϕ, N) -module with descent data $D(\chi, \tilde{c})$ over $K_0 \otimes_{\mathbb{Q}_p} E$ with generator \mathbf{v} ,

$$\text{Fil}^i(K \otimes_{K_0} D(\chi, \tilde{c})) = \begin{cases} K \otimes_{K_0} D(\chi, \tilde{c}) & \text{if } i \leq 1 \\ 0 & \text{if } i > 1 \end{cases}$$

and

$$\phi(v) = p\tilde{c}\mathbf{v}, \quad N = 0, \quad \hat{g} \cdot \mathbf{v} = (1 \otimes \chi(g))\mathbf{v}.$$

Now there is a strongly divisible \mathcal{O}_E -module $\mathcal{M}(\chi, \tilde{c})$ contained in $S \otimes_{W(k)} D(\chi, \tilde{c})$ generated by \mathbf{v} and satisfying

$$\text{Fil}^1 \mathcal{M}(\chi, \tilde{c}) = \mathcal{M}(\chi, \tilde{c}), \quad \phi_1(\mathbf{v}) = \tilde{c}\mathbf{v}, \quad \hat{g} \cdot \mathbf{v} = (1 \otimes \chi(g))\mathbf{v}.$$

In particular $\mathcal{M}(\chi, \tilde{c})/\mathfrak{m}_E \mathcal{M}(\chi, \tilde{c}) = \mathcal{M}(\bar{\chi}, c)$. One checks (exactly as in [Sav05, Ex. 2.14]) that $D_{\text{st},2}^K(\chi) = D(\chi, 1)$, and it is then standard that the representation giving rise to $D(\chi, \tilde{c})$ is an unramified twist of χ . The result now follows from the discussion of the functor $T_{\text{st},2}^L$ immediately before the statement of the lemma. \square

5.2. Actual weights are predicted weights. In this section we make use of the results of [Sav06] to prove results on the possible forms of Galois representations which are modular of a specified weight. Suppose that $\bar{\rho}$ is modular of weight $\sigma_{m,n}$. Then by Lemma 3.4, $\bar{\rho}|_{G_{\mathbb{F}_p}}$ has a potentially semistable lift of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$.

Lemma 5.3. *If $\bar{\rho}$ is modular of weight $\sigma_{m,n}$, then $\det \bar{\rho}|_{I_{\mathbb{F}_p}} = \omega^{2m+n+e}$.*

Proof. As remarked above, $\bar{\rho}|_{G_{F_p}}$ has a potentially semistable lift of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$, say ρ . It suffices to check that $\det \rho|_{I_{F_p}} = \varepsilon \tilde{\omega}^{2m+n}$, where ε is the p -adic cyclotomic character (recalling again that the reduction mod p of ε is ω^e). This follows at once from Definition 3.2 and the results of section B.2 of [CDT99]. \square

We begin by addressing the case when $\bar{\rho}|_{G_{F_p}}$ is reducible.

Lemma 5.4. *Suppose that $\bar{\rho}$ is modular of weight $\sigma_{m,n}$, and that $\bar{\rho}|_{G_{F_p}}$ is reducible.*

*Then $\bar{\rho}|_{I_{F_p}} \cong \begin{pmatrix} \omega^{m+n+x} & * \\ 0 & \omega^{m+e-x} \end{pmatrix}$ or $\bar{\rho}|_{I_{F_p}} \cong \begin{pmatrix} \omega^{m+e-x} & * \\ 0 & \omega^{m+n+x} \end{pmatrix}$ for some $1 \leq x \leq e$.*

Proof. We consider first the case $n = p - 1$. By Lemma 3.4, $\bar{\rho}|_{G_{F_p}}$ has a potentially semistable lift of type $\tilde{\omega}^m \oplus \tilde{\omega}^m$. If it is not potentially crystalline then it is automatically ordinary, and the result follows immediately (with $x = e$). If this lift is in fact potentially crystalline then without loss of generality we may twist and suppose that $m = 0$, and thus that $\bar{\rho}$ has a crystalline lift of Hodge-Tate weights 0 and 1. Then $\bar{\rho}|_{G_{F_p}}$ is flat, and the result follows at once from Lemma 5.3 and Theorem 3.4.3 of [Ray74].

For the remainder of the proof suppose that $n < p - 1$. Let K_0 be the unramified quadratic extension of F_p , and let $K = K_0(\varpi)$ with $\varpi = \pi_p^{1/(p^2-1)}$. Let k_2 denote the residue field of K_0 , and if $g \in \text{Gal}(K/F_p)$ define $\bar{\eta}(g)$ to be the image of $g(\varpi)/\varpi$ in k_2 .

By Lemma 3.4, $\bar{\rho}|_{G_{F_p}}$ has a lift to a potentially Barsotti-Tate representation of type $\tilde{\omega}_{\sigma_1}^{m+n+1} \tilde{\omega}_{\sigma_2}^{m-1} \oplus \tilde{\omega}_{\sigma_1}^{m-1} \tilde{\omega}_{\sigma_2}^{m+n+1}$, and we may suppose this lift to be valued in \mathcal{O}_E for E some finite extension of \mathbb{Q}_p with residue field k_E into which k_2 embeds, and with uniformiser π_E . The lift becomes Barsotti-Tate over K , and the π_E -torsion in the corresponding p -divisible group gives rise to a finite flat k_E -module scheme \mathcal{G} over \mathcal{O}_K with descent data to F_p , with generic fibre $\bar{\rho}|_{G_{F_p}}$, such that the descent data to K_0 is $\omega_{\sigma_1}^{m+n+1} \omega_{\sigma_2}^{m-1} \oplus \omega_{\sigma_1}^{m-1} \omega_{\sigma_2}^{m+n+1}$. We claim that this implies the lemma.

Suppose that $\bar{\rho}|_{G_{F_p}} \cong \begin{pmatrix} \psi_1 & * \\ 0 & \psi_2 \end{pmatrix}$. Then by a scheme-theoretic closure argument, \mathcal{G} must contain a finite flat subscheme \mathcal{G}_1 with descent data which has generic fibre ψ_1 . Twisting by a suitable power of ω , we may assume $m = 0$. By Theorem 3.5 of [Sav06], we may write the Breuil module \mathcal{M} corresponding to \mathcal{G}_1 in the form

- $\mathcal{M} = ((k_2 \otimes_{\mathbb{F}_p} k_E)[u]/u^{e(p^2-1)p}) \cdot w$
- $\text{Fil}^1 \mathcal{M} = u^r \mathcal{M}$
- $\phi_1(u^r w) = cw$ for some $c \in (k \otimes_{\mathbb{F}_p} k_E)^\times$
- $\hat{g}(w) = (\bar{\eta}(g)^\kappa \otimes 1)w$ for $g \in \text{Gal}(K/F_p)$.

Here κ, r are integers with $\kappa \in [0, p^2 - 1]$ and $r \in [0, e(p^2 - 1)]$ satisfying $\kappa \equiv p(\kappa + r) \pmod{p^2 - 1}$ or equivalently $r \equiv (p - 1)\kappa \pmod{p^2 - 1}$. From the shape of the descent data κ must be congruent to one of $n + 1 - p$ or $-1 + p(n + 1) \pmod{p^2 - 1}$; hence $\kappa = n + p^2 - p$ or $pn + (p - 1)$.

In the first case we find $r \equiv (p - 1)(n + 2) \pmod{p^2 - 1}$, and therefore $r = (p - 1)(n + 2) + y(p^2 - 1)$ for some $0 \leq y < e$. One checks that there is a map $f : \mathcal{M}(\omega^{n+y+1}, c) \rightarrow \mathcal{M}$ mapping $v \mapsto u^{pr/(p-1)}w$, where $\mathcal{M}(\omega^{n+y+1}, c)$ is as defined

in Lemma 5.2. The kernel of this map does not contain any free $k_2[u]/u^{e(p^2-1)}$ -submodules, and so by [Sav04, Prop 8.3] the map f induces an isomorphism on generic fibres. By Lemma 5.2 we deduce that $\psi_1|_{I_{F_p}} = \omega^{n+x}$ with $x = y+1 \in [1, e]$.

In the second case we find $r \equiv (p-1)(p-n-1) \pmod{p^2-1}$, and therefore $r = (p-1)(p-n-1) + y(p^2-1)$ for some $0 \leq y < e$. One checks that there is a map $\mathcal{M}(\omega^y, c) \rightarrow \mathcal{M}$ mapping $v \mapsto u^{pr/(p-1)}w$. As in the previous case this map induces an isomorphism on generic fibres, and by Lemma 5.2 we deduce that $\psi_1|_{I_{F_p}} = \omega^{e-x}$ with $x = e-y \in [1, e]$.

Now in either of the two cases the result follows from Lemma 5.3. \square

We now consider the irreducible case.

Lemma 5.5. *Suppose that $\bar{\rho}$ is modular of weight $\sigma_{m,n}$, and that $\bar{\rho}|_{G_{F_p}}$ is irreducible. Then $\bar{\rho}|_{I_{F_p}} \cong \omega_{\sigma_1}^{m+n+x} \omega_{\sigma_2}^{m+e-x} \oplus \omega_{\sigma_1}^{m+e-x} \omega_{\sigma_2}^{m+n+x}$ for some $1 \leq x \leq e$.*

Proof. This may be proved in essentially the same way as Lemma 5.4. However, the result follows easily from the results of [Sch08a]. Note that $\sigma_{m,n}$ is a Jordan-Hölder factor of $\det^m \otimes \text{Ind}(\delta^n)$. Then in the case $n \neq 0$, $p-1$ the result follows at once from (the proof of) Proposition 3.3 of [Sch08a]; while Schein works in the case of an indefinite quaternion algebra, his arguments are ultimately purely local, using Raynaud's classification of finite flat group schemes of type (p, \dots, p) .

In the case $n = 0$ or $p-1$ a very similar but rather easier analysis applies. In this case, by Lemma 3.4, $\bar{\rho}|_{G_{F_p}}$ has a potentially semistable lift of type $\tilde{\omega}^m \oplus \tilde{\omega}^m$. If it is not potentially crystalline then it is automatically ordinary, a contradiction. Thus the lift must in fact be potentially crystalline, and after twisting, one needs only to consider the case $m = 0$, and one is reduced to determining the possible generic fibres of finite flat group schemes over F_p , which is immediate from Raynaud's analysis (Theorem 3.4.3 of [Ray74]), together with Lemma 5.3. \square

Putting Lemma 5.4 and Lemma 5.5 together, we obtain the following.

Corollary 5.6. *If $\bar{\rho}|_{G_{F_p}}$ is semisimple, and $\bar{\rho}$ is modular of weight σ , then $\sigma \in W^?(\bar{\rho})$.*

Note that if $e \geq p-1$ then $W^?(\bar{\rho})$ is precisely the set of weights $\sigma_{m,n}$ with $\det \bar{\rho}|_{I_{F_p}} = \omega^{2m+n+e}$, so the result follows from Lemma 5.3 alone.

6. LOCAL LIFTS

If $\bar{\rho}$ is to be modular of weight $\sigma \in W^?(\bar{\rho})$, then Lemma 3.4 entails that $\bar{\rho}|_{G_{F_p}}$ must have a potentially Barsotti-Tate lift of some particular type or types. The existence of certain of these local lifts will be a key ingredient in the proof that $\bar{\rho}$ is indeed modular of weight σ . Our aim in this section is to produce these lifts.

6.1. The niveau 1 case. Let K be a finite extension of \mathbb{Q}_p , and let S_K denote the set of embeddings $\tau : K \hookrightarrow \overline{\mathbb{Q}_p}$.

Definition 6.1. If ρ is a $\overline{\mathbb{Q}_p}$ -valued crystalline representation of G_K and $\tau \in S_K$ we say that the Hodge-Tate weights of ρ with respect to τ are the i for which

$$gr_{\tau}^{-i}(\rho) := gr^{-i}((\rho \otimes_{\mathbb{Q}_p} \text{B}_{\text{dR}})^{G_K} \otimes_{\overline{\mathbb{Q}_p} \otimes_{\mathbb{Q}_p} K, 1 \otimes \tau} \overline{\mathbb{Q}_p}) \neq 0,$$

counted with multiplicity $\dim gr_{\tau}^{-i}(\rho)$. We denote the multiset of Hodge-Tate weights of ρ with respect to τ by $\text{HT}_{\tau}(\rho)$; it has cardinality $\dim \rho$.

If $\sigma \in S_K$, we let $\bar{\sigma}$ be the induced element of S_k .

Lemma 6.2. *Let $A = \{a_\tau\}_{\tau \in S_K}$ be a set of positive integers. Then there is a crystalline character ε_A^K of G_K such that $HT_\tau(\varepsilon_A^K) = a_\tau$ for all $\tau \in S_K$, and ε_A^K is unique up to unramified twist. Furthermore, $\varepsilon_A^K|_{I_K} = \prod_{\tau \in S_k} \omega_\tau^{b_\tau}$, where*

$$b_\tau = \sum_{\sigma \in S_K: \bar{\sigma} = \tau} a_\sigma.$$

Proof. This is straightforward, and we only sketch a proof; the full details will appear in [GS]. The existence of ε_A^K is easy, as one has only to write down the corresponding weakly admissible filtered module. Uniqueness up to unramified twist is clear, because a crystalline character all of whose Hodge-Tate weights are 0 is automatically unramified. Finally, to compute the reduction modulo p , it suffices to treat the case where all but one element of A is 0, and the remaining element is 1, as the general case then follows by taking a product of such characters. In this case one can compute the reduction mod p by using strongly divisible modules and Breuil modules, as in [Sav06]. \square

Lemma 6.3. *Suppose that*

$$\bar{\rho}|_{I_{F_p}} \cong \begin{pmatrix} \omega^{m+n+x} & 0 \\ 0 & \omega^{m+e-x} \end{pmatrix}$$

with $1 \leq x \leq e$, and that $\bar{\rho}|_{G_{F_p}}$ itself is decomposable (which is automatic if $\omega^{m+n+x} \neq \omega^{m+e-x}$). Then $\bar{\rho}|_{G_{F_p}}$ has a potentially Barsotti-Tate lift ρ of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$. If $x \neq e$ then there is a non-ordinary such lift; if $x = e$ then there is a non-ordinary such lift provided that $n + e > p - 1$, unless $e \leq p - 1$ and $n = p - 1$.

Proof. Let $A = \{a_\tau\}_{\tau \in S_{F_p}}$ have exactly x elements equal to 1, and the remaining $e - x$ elements equal to 0. Let $B = \{1 - a_\tau\}_{\tau \in S_{F_p}}$. Then by Lemma 6.2 we may take ρ to be given by an unramified twist of $\tilde{\omega}^{m+n} \varepsilon_A^{F_p}$ plus an unramified twist of $\tilde{\omega}^m \varepsilon_B^{F_p}$ (with the unramified twists chosen so that this is indeed a lift of $\bar{\rho}$). This lift is ordinary precisely if one of $\varepsilon_A^{F_p}$ or $\varepsilon_B^{F_p}$ is an unramified twist of the cyclotomic character, which occurs if and only if $x = e$.

Now suppose that $x = e$. If $e > p - 1$, then because $\omega^{p-1} = 1$ we may instead take A to have exactly $x - (p - 1)$ elements equal to 1, and the rest equal to 0, and produce a non-ordinary lift with B and ρ defined as above. If $e \leq p - 1$ but $n + e > p - 1$, we take A to have exactly $n + e - (p - 1)$ elements equal to 1 and the rest equal to zero. Set $B = \{1 - a_\tau\}_{\tau \in S_{F_p}}$ and take ρ to be given by an unramified twist of $\tilde{\omega}^m \varepsilon_A^{F_p}$ plus an unramified twist of $\tilde{\omega}^{m+n} \varepsilon_B^{F_p}$. This is non-ordinary provided that $n \neq p - 1$. \square

6.2. The niveau 2 case: some strongly divisible modules. In the remainder of the section we wish to prove the following.

Lemma 6.4. *Suppose that $\bar{\rho}|_{G_{F_p}}$ is irreducible and $\bar{\rho}|_{I_{F_p}} \cong \omega_{\sigma_1}^{m+n+x} \omega_{\sigma_2}^{m+e-x} \oplus \omega_{\sigma_1}^{m+e-x} \omega_{\sigma_2}^{m+n+x}$ for some $1 \leq x \leq e$. Then $\bar{\rho}|_{G_{F_p}}$ has a potentially Barsotti-Tate lift of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$.*

We prepare for the proof of the Lemma 6.4 by constructing certain strongly divisible modules.

Let K be a totally ramified finite extension of \mathbb{Q}_p with ramification index e and residue field k , and fix a uniformiser π of K . Let K_2 be the splitting field of $u^{p^2-1} - \pi$, and write $e_2 = (p^2 - 1)e$ and k_2 respectively for the ramification index and residue field of K_2 . Similarly write $e_1 = (p - 1)e$. Choose $\varpi \in K_2$ a uniformiser with $\varpi^{p^2-1} = \pi$. Let $E(u)$ be an Eisenstein polynomial for ϖ , and write $E(u) = u^{e_2} + pF(u)$, so that $F(u)$ is a polynomial in u^{p^2-1} over $W(k)$ whose constant term is a unit.

If $g \in G_K$ write $\tilde{\omega}_2(g) = g\varpi/\varpi \in \mu_{p^2-1}(K_2)$ and write $\omega_2(g)$ for the image of $\tilde{\omega}_2(g)$ in k_2 . Set $\tilde{\omega} = \tilde{\omega}_2^{p+1}$ and $\omega = \omega_2^{p+1}$. These may all equally well be regarded as functions on $\text{Gal}(K_2/K)$. Note that if $\sigma : k_2 \hookrightarrow \overline{\mathbb{F}}_p$ then in the notation of previous sections we have $\omega_\sigma = \sigma \circ \omega_2|_{I_{K_2}}$. We will abuse notation and also write $\tilde{\omega}$ for $\tilde{\omega}|_{I_K}$, the Teichmüller lift of a fundamental character of level one of K .

Let E denote the coefficient field for our representations, with integer ring \mathcal{O}_E and maximal ideal \mathfrak{m}_E . Assume that E is ramified and that $W(k_2)$ embeds into E . Let k_E denote the residue field of E , and assume without loss of generality that k_E is contained in $\overline{\mathbb{F}}_p$. Write $S = S_{K_2, \mathcal{O}_E}$ (notation as in [Sav05, Sec. 4]). Recall that $\phi : S \rightarrow S$ is the $W(k_2)$ -semilinear, \mathcal{O}_E -linear map sending $u \mapsto u^p$. The group $\text{Gal}(K_2/K)$ acts $W(k_2)$ -semilinearly on S via $g \cdot u = (\tilde{\omega}_2(g) \otimes 1)u$. Set $c = \frac{1}{p}\phi(E(u)) \in S^\times$.

Theorem 6.5. *Let $0 \leq j \leq e_1$ be an integer and set $J = (p + 1)j$. There exists a strongly divisible \mathcal{O}_E -module $\mathcal{M} = \mathcal{M}_j$ with tame descent data from K_2 to K and generators g_1, g_2 such that $\overline{\mathcal{M}} = \mathcal{M}/\mathfrak{m}_E\mathcal{M}$ has the form*

$$\begin{aligned} \text{Fil}^1\mathcal{M} &= \langle u^J \bar{g}_1, u^{e_2-J} \bar{g}_2 \rangle, \\ \phi_1(u^J \bar{g}_1) &= \bar{g}_2, \quad \phi_1(u^{e_2-J} \bar{g}_2) = \bar{g}_1, \\ \widehat{g}(\bar{g}_1) &= \bar{g}_1, \quad \widehat{g}(\bar{g}_2) = \omega^n(g) \bar{g}_2 \end{aligned}$$

for $g \in \text{Gal}(K_2/K)$, where n is the least nonnegative residue of j modulo $p - 1$.

Proof. Choose any $x_1, x_2 \in \mathfrak{m}_E$ with $x_1 x_2 = p$. Let \mathcal{M} be the S -module generated by g_1, g_2 and let $\text{Fil}^1\mathcal{M}$ be the submodule of \mathcal{M} generated by

$$h_1 := u^J g_1 + x_1 g_2, \quad h_2 := -x_2 F(u) g_1 + u^{e_2-J} g_2, \quad (\text{Fil}^1 S)\mathcal{M}.$$

We would like to define a map $\phi : \mathcal{M} \rightarrow \mathcal{M}$, semilinear with respect to ϕ on S , so that $\phi_1 = \frac{1}{p}\phi|_{\text{Fil}^1\mathcal{M}}$ is well-defined and satisfies

$$(6.2.1) \quad \phi_1(u^J g_1 + x_1 g_2) = g_2$$

$$(6.2.2) \quad \phi_1(-x_2 F(u) g_1 + u^{e_2-J} g_2) = g_1.$$

This entails $\phi_1(E(u)g_1) = \phi_1(u^{e_2-J} h_1 - x_1 h_2) = u^{p(e_2-J)} g_2 - x_1 g_1$, suggesting that we should define

$$\phi(g_1) = c^{-1}(u^{p(e_2-J)} g_2 - x_1 g_1)$$

and similarly

$$\phi(g_2) = c^{-1}(x_2 \phi(F(u))g_2 + u^{pJ} g_1).$$

Extending this map ϕ -semilinearly to all of \mathcal{M} , one checks that equations (6.2.1) and (6.2.2) hold, so that $\phi(\text{Fil}^1\mathcal{M})$ is contained in $p\mathcal{M}$ and generates it over S .

Recall that each element of S can be written uniquely as $\sum_{i \geq 0} r_i(u)E(u)^i/i!$ where each r_i is a polynomial of degree less than e_2 , and such an element lies in $\text{Fil}^1 S$ if and only if $r_0 = 0$. We claim that each coset in $\text{Fil}^1\mathcal{M}/(\text{Fil}^1 S)\mathcal{M}$ has a

representative $ah_1 + bh_2$ with a, b polynomials of degree less than $e_2 - J$ and J respectively. Indeed, given a coset $Ah_1 + Bh_2 + (\text{Fil}^1 S)\mathcal{M}$ with $A, B \in S$, we can alter the coset representative as follows: write B as the sum of a polynomial of degree less than e_2 and an element of $\text{Fil}^1 S$, and absorb h_2 times the latter into $(\text{Fil}^1 S)\mathcal{M}$; use the relation $u^J h_2 = E(u)g_2 - x_2 F(u)h_1$ to eliminate the terms in B of degree at least J (thus altering the coefficient of h_1); write the new coefficient of h_1 as the sum of a polynomial of degree less than e_2 and an element of $\text{Fil}^1 S$, and absorb the latter into $(\text{Fil}^1 S)\mathcal{M}$; finally, use the relation $u^{e_2 - J} h_1 = E(u)g_1 + x_1 h_2$ to eliminate the terms of degree at least $e_2 - J$ in the coefficient of h_1 , noting that in this last step one does not re-introduce terms of degree at least u^J into the coefficient of h_2 .

We are now ready check that if I is any ideal of \mathcal{O}_E , then $\text{Fil}^1 \mathcal{M} \cap I\mathcal{M} = I\text{Fil}^1 \mathcal{M}$. We have seen that an arbitrary element m of $\text{Fil}^1 \mathcal{M}$ has the form $m = ah_1 + bh_2 + s_1 g_1 + s_2 g_2$ with $s_1, s_2 \in \text{Fil}^1 S$ and a, b polynomials of degree less than $e_2 - J$ and J respectively. Suppose such an element lies in $I\mathcal{M}$. The coefficient of g_2 for this element is $x_1 a + u^{e_2 - J} b + s_2$. This must lie in IS ; but because an element $\sum_i r_i(u)E(u)^i/i!$ (with $\deg(r_i) < e_2$ for all i) lies in IS if and only if all the coefficients of the polynomials r_i lie in $W(k_2) \otimes I$, and because $x_1 a, u^{e_2 - J} b$ have no terms in common of the same degree, it follows that $s_2 \in I(\text{Fil}^1 S)$ and the coefficients of b lie in $W(k_2) \otimes I$. Then $ah_1 + s_1 g_1$ still lies in $I\mathcal{M}$, and now we can see that $s_1 \in I(\text{Fil}^1 S)$ and the coefficients of a lie in $W(k_2) \otimes I$. We conclude that $m \in I(\text{Fil}^1 \mathcal{M})$, as desired.

Next we turn to descent data. If $g \in \text{Gal}(K_1/K)$, set $\widehat{g}(g_1) = g_1$ and $\widehat{g}(g_2) = \tilde{\omega}^n(g)g_2$, and extend \widehat{g} to \mathcal{M} semilinearly with respect to the usual action of g on S . One sees that \widehat{g} preserves $\text{Fil}^1 \mathcal{M}$ (remember that $F(u)$ is a polynomial in $u^{p^2 - 1}$ over $W(k)$) and commutes with ϕ . So, summarizing all our work so far, we have shown that the tuple $(\mathcal{M}, \text{Fil}^1 \mathcal{M}, \phi, \{\widehat{g}\})$ satisfies all the axioms of a strongly divisible \mathcal{O}_E -module with tame descent data [Sav05, Def. 4.1] other than the axioms involving the monodromy operator N .

Ignoring the action of \mathcal{O}_E and the descent data and regarding $(\mathcal{M}, \text{Fil}^1 \mathcal{M}, \phi)$ simply as a strongly divisible \mathbb{Z}_p -module over K_2 , it follows from [Bre00, Prop 5.1.3(1)] that there exists a *unique* $W(k_2) \otimes \mathbb{Z}_p$ -endomorphism $N : \mathcal{M} \rightarrow \mathcal{M}$ satisfying axioms (5)-(8) of [Sav05, Def. 4.1], except that we have axiom (5) only with respect to $s \in S_{K_2, \mathbb{Z}_p}$ until we know that N commutes with the action \mathcal{O}_E . For the latter, if $z \in \mathcal{O}_E^\times$ we observe that zNz^{-1} satisfies the same list of axioms that determines N uniquely, so z and N commute; since \mathcal{O}_E^\times generates \mathcal{O}_E as a \mathbb{Z}_p -module we conclude that N is an \mathcal{O}_E -endomorphism. To conclude that \mathcal{M} (with its associated structures) is a strongly divisible \mathcal{O}_E -module, the only thing left is to confirm the remainder of axiom (12), that N commutes with \widehat{g} for each $g \in \text{Gal}(K_2/K)$; for this, use the same argument as in the previous sentence, this time applied to $\widehat{g}N\widehat{g}^{-1}$.

That $\overline{\mathcal{M}} = \mathcal{M}/\mathfrak{m}_E \mathcal{M}$ has the desired form is obvious. \square

Define $\rho_j = T_{\text{st}, 2}^K(\mathcal{M}_j)$, the potentially Barsotti-Tate Galois representation associated to \mathcal{M}_j .

Proposition 6.6. *The representation ρ_j has inertial type $\tilde{\omega}^n \oplus 1$.*

Proof. Let D denote the filtered module with descent data associated to ρ_j . We recall from the proof of [Sav05, Lem. 3.13] that D is equal to the kernel of N on $W(k_2)[1/p] \otimes_{W(k_2)} \mathcal{M}_j$.

Write $M = \mathcal{M}_j/u\mathcal{M}_j$ and equip M with the maps N and ϕ induced from \mathcal{M}_j (so in particular $N = 0$ on M), as well as induced descent data \widehat{g} . By [Bre97, Prop. 6.2.1.1] the canonical map $\mathcal{M}_j \rightarrow M$ has a unique $W(k_2)[1/p]$ -linear section $s : M \rightarrow \mathcal{M}_j$ preserving ϕ and N ; then the same uniqueness argument as in the last paragraph of the proof of Theorem 6.5 shows that s is an E -linear map and that s preserves descent data.

Recalling that $N = 0$ on M , we see that $D = \text{im}(s)$, so in particular D has a $W(k_2)[1/p] \otimes_{\mathbb{Q}_p} E$ -basis v_1, v_2 with $v_i = s(g_i)$. Since s preserves descent data we have $\widehat{g} \cdot v_1 = v_1$ and $\widehat{g} \cdot v_2 = \tilde{\omega}^n(g)v_2$. The proposition follows. \square

6.3. The niveau 2 case: conclusion of the proof. We will now compute $\bar{\rho}_j = T_{\text{st},2}^K(\mathcal{M}_j/\mathfrak{m}_E\mathcal{M}_j)$, which by [Sav05, Prop 4.13] is the reduction mod p of ρ_j . More precisely we will compute $\bar{\rho}_j|_{G_L}$ where L is the unramified quadratic extension of K contained in K_2 .

As in Lemma 5.2 let $\bar{\chi} : \text{Gal}(K_2/L) \rightarrow k_E^\times$ be a character and let $\mathcal{M}(\bar{\chi})$ denote the rank one Breuil module with k_E -coefficients and descent data from K_2 to L with generator v and

$$\text{Fil}^1 \mathcal{M}(\bar{\chi}) = \mathcal{M}(\bar{\chi}), \quad \phi_1(v) = v, \quad \widehat{g}(v) = (1 \otimes \bar{\chi}(g))v$$

for $g \in \text{Gal}(K_2/L)$. By Lemma 5.2 we have

$$(6.3.1) \quad T_{\text{st},2}^L(\mathcal{M}(\bar{\chi})) = \bar{\chi}.$$

Let $\overline{\mathcal{M}}_j^2$ denote the Breuil module $\overline{\mathcal{M}}_j = \mathcal{M}_j/\mathfrak{m}_E\mathcal{M}_j$ with its descent data restricted to $\text{Gal}(K_2/L)$, so that $T_{\text{st},2}^L(\overline{\mathcal{M}}_j^2) = T_{\text{st},2}^K(\overline{\mathcal{M}}_j)|_{G_L}$. We abuse notation and also let ω_σ denote $\sigma \circ \omega_2|_{G_L}$.

Proposition 6.7. *We have $\bar{\rho}_j|_{G_L} = T_{\text{st},2}^L(\overline{\mathcal{M}}_j^2) \cong \omega_{\sigma_1}^{j+e} \oplus \omega_{\sigma_2}^{j+e}$.*

Proof. Let $e_{\sigma_1}, e_{\sigma_2} \in k_2 \otimes k_E$ denote the idempotents corresponding to the embeddings $\sigma_1, \sigma_2 : k_2 \hookrightarrow k_E$, so that $e_{\sigma_i}(a \otimes 1) = e_{\sigma_i}(1 \otimes \sigma_i(a))$. Suppose $\{\alpha, \beta\} = \{1, 2\}$. If one ignores descent data, one checks that there is a map $f_\beta : \mathcal{M}(\bar{\chi}) \rightarrow \overline{\mathcal{M}}_j^2$ obtained by sending

$$v \mapsto u^{p(j+e)}e_{\sigma_\alpha}g_1 + u^{p(pe-j)}e_{\sigma_\beta}g_2.$$

In order that this map be compatible with descent data, one checks that it is necessary and sufficient that $e_{\sigma_\alpha}(1 \otimes \bar{\chi}) = e_{\sigma_\alpha}(\omega_2^{p(j+e)} \otimes 1)$, i.e., $\bar{\chi} = \omega_{\sigma_\alpha}^{p(j+e)} = \omega_{\sigma_\beta}^{j+e}$. We therefore have a map

$$f_1 \oplus f_2 : \mathcal{M}(\omega_{\sigma_1}^{j+e}) \oplus \mathcal{M}(\omega_{\sigma_2}^{j+e}) \rightarrow \overline{\mathcal{M}}_j^2.$$

Note that $\ker(f_1 \oplus f_2)$ does not contain any free $k_2[u]/u^{e_2p}$ -submodules (this amounts to the fact that $p(j+e)$ and $p(pe-j)$ are both smaller than pe_2); by [Sav04, Prop 8.3] we deduce that $f_1 \oplus f_2$ induces an isomorphism on Galois representations, and the proposition follows from (6.3.1). \square

Finally we have the following.

Proof of Lemma 6.4. Take $K = F_p$ in the discussion of this and the previous subsection. Twisting by a suitable power of the (Teichmüller lift of) a fundamental character of level one, we may assume $m = 0$. Setting $j = n + (p - 1)(e - x)$, one checks that $\omega_{\sigma_1}^{j+e} = \omega_{\sigma_1}^{n+x} \omega_{\sigma_2}^{e-x}$ and similarly for $\omega_{\sigma_2}^{j+e}$. It follows from Proposition 6.7 that $\bar{\rho}$ is an unramified twist of $\bar{\rho}_j$. Therefore a suitable unramified twist of ρ_j will lift $\bar{\rho}$, and since ρ_j has type $\tilde{\omega}^n \oplus 1$ we are done. \square

Remark 6.8. The reader may find it unnatural that although ρ_j becomes Barsotti-Tate over $K_1 = K(\pi^{1/(p-1)})$, we instead work with a strongly divisible module over K_2 for ρ_j (because our method for computing $\bar{\rho}_j|_{G_L}$ requires it). One can certainly write down the strongly divisible module over K_1 instead (just replace J and e_2 with j and e_1 throughout the construction of \mathcal{M}_j), whose reduction mod p corresponds to a group scheme \mathcal{G} over \mathcal{O}_{K_1} with generic fibre descent data from K_1 to K . One can then hope to show directly, by extending the methods of [BCDT01, Sec. 5.4], that $\mathcal{G} \times_{\mathcal{O}_{K_1}} \mathcal{O}_{K_2}$ (with generic fibre descent data from K_2 to K) corresponds to our $\overline{\mathcal{M}}_j$. However, this last step would require at least several extra pages of rather technical work, so we prefer to proceed as above instead.

7. THE MAIN THEOREMS

We now prove the main results of this paper, by combining the techniques of earlier sections with the lifting machinery of Khare-Wintenberger, as interpreted by Kisin. In particular, we use the following result.

Theorem 7.1. *Suppose that $p > 2$ and that $\bar{\rho} : G_F \rightarrow \mathrm{GL}_2(\overline{\mathbb{F}}_p)$ is modular. If $p = 5$ and the projective image of $\bar{\rho}$ is isomorphic to $\mathrm{PGL}_2(\mathbb{F}_5)$, assume further that $[F(\zeta_p) : F] = 4$.*

- *Suppose that $\bar{\rho}|_{G_{F_p}}$ has a non-ordinary potentially Barsotti-Tate lift of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$. Then $\bar{\rho}$ has a modular lift which is potentially Barsotti-Tate of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$ and non-ordinary.*
- *Suppose that $\bar{\rho}$ has an ordinary modular lift. Suppose also that $\bar{\rho}|_{G_{F_p}}$ has a ordinary potentially Barsotti-Tate lift of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$. Then $\bar{\rho}$ has a modular lift which is potentially Barsotti-Tate of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$ and ordinary.*

Proof. This is a special case of Corollary 3.1.7 of [Gee06a]. \square

In combination with the local computations of section 6, this shows us that if $\bar{\rho}|_{G_{F_p}}$ is semisimple, and $\sigma_{m,n} \in W^?(\bar{\rho})$, then $\bar{\rho}$ has a modular lift which is potentially Barsotti-Tate of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^n$. By Lemma 3.4, this means that $\bar{\rho}$ is modular of weight $\sigma_{m,n}$ or $\sigma_{m+n,p-1-n}$. However, we can frequently guarantee that this lift is non-ordinary, and the weight cycling techniques of section 4 then give the following far more useful result.

Theorem 7.2. *Suppose that $p > 2$ and that $\bar{\rho} : G_F \rightarrow \mathrm{GL}_2(\overline{\mathbb{F}}_p)$ is modular. If $p = 5$ and the projective image of $\bar{\rho}$ is isomorphic to $\mathrm{PGL}_2(\mathbb{F}_5)$, assume further that $[F(\zeta_p) : F] = 4$. If $\bar{\rho}|_{G_{F_p}}$ has a non-ordinary potentially Barsotti-Tate lift of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$, $0 \leq n \leq p - 1$, then $\bar{\rho}$ is modular both of weight $\sigma_{m,n}$ and of weight $\sigma_{m+n,p-1-n}$.*

Proof. By Theorem 7.1, there is a modular lift of $\bar{\rho}$ which is potentially Barsotti-Tate of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$, and which is non-ordinary. The result follows from Proposition 4.4. \square

We now extract some consequences from this result. Suppose that $\bar{\rho}|_{G_{F_p}}$ is semisimple. Then we have already proved that $W(\bar{\rho})$, the set of weights σ for which $\bar{\rho}$ is modular of weight σ , is contained in $W^2(\bar{\rho})$ (this is Corollary 5.6). We can frequently deduce the converse implication, showing that if $\sigma_{m,n} \in W^2(\bar{\rho})$ then $\sigma_{m,n} \in W(\bar{\rho})$. By Theorem 7.2 it suffices to be able to produce a non-ordinary potentially Barsotti-Tate lift of $\bar{\rho}|_{G_{F_p}}$ of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$. In the majority of cases we constructed such a lift in section 6, and we obtain the following result.

Corollary 7.3. *Suppose that $p > 2$ and that $\bar{\rho} : G_F \rightarrow \mathrm{GL}_2(\overline{\mathbb{F}}_p)$ is modular. If $p = 5$ and the projective image of $\bar{\rho}$ is isomorphic to $\mathrm{PGL}_2(\mathbb{F}_5)$, assume further that $[F(\zeta_p) : F] = 4$. Suppose that $\bar{\rho}|_{G_{F_p}}$ is semisimple.*

- (1) *If $\bar{\rho}|_{G_{F_p}}$ is irreducible or $e \geq p$, then $\bar{\rho}$ is modular of weight σ if and only if $\sigma \in W^2(\bar{\rho})$.*
- (2) *If $e \leq p - 1$, then $\bar{\rho}$ is modular of weight σ if and only if $\sigma \in W^2(\bar{\rho})$ except possibly if $\sigma = \sigma_{m,n}$ and*

$$\bar{\rho}|_{I_{F_p}} \cong \begin{pmatrix} \omega^{m+n+e} & 0 \\ 0 & \omega^m \end{pmatrix}$$

with $n + e \leq p - 1$ or $n = p - 1$.

Proof. As already remarked, the ‘‘only if’’ direction is Corollary 5.6, and the ‘‘if’’ direction follows at once from Theorem 7.2, Lemma 6.3, Lemma 6.4, and Definition 5.1. In part (2), the exceptional cases are precisely the ones where we were unable to construct a non-ordinary lift in Lemma 6.3. \square

Note that there are at most four exceptional cases in part (2) of Corollary 7.3: there are two ways of ordering the diagonal characters, and each ordering will correspond either to one or two values of n (if $n \not\equiv 0$ or $n \equiv 0 \pmod{p-1}$ respectively).

In fact, if we assume in addition that $\bar{\rho}$ has an ordinary modular lift, then we are able to dispose of most of these exceptional cases. This relies on something of a combinatorial coincidence; it turns out that in most cases where $\sigma_{m,n} \in W^2(\bar{\rho})$ but $\bar{\rho}|_{G_{F_p}}$ has only ordinary lifts of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$, then $\sigma_{m+n, p-1-n} \notin W^2(\bar{\rho})$, so the combination of Theorem 7.1, Lemma 3.4 and Corollary 5.6 shows that in fact $\sigma_{m,n} \in W(\bar{\rho})$.

Corollary 7.4. *Suppose that $p > 2$ and that $\bar{\rho} : G_F \rightarrow \mathrm{GL}_2(\overline{\mathbb{F}}_p)$ is modular. Suppose that $e \leq p - 1$ and that $\bar{\rho}|_{G_{F_p}}$ is semisimple and reducible. Suppose further that $\bar{\rho}$ has an ordinary modular lift. If $p = 5$ and the projective image of $\bar{\rho}$ is isomorphic to $\mathrm{PGL}_2(\mathbb{F}_5)$, assume further that $[F(\zeta_p) : F] = 4$. Suppose that $\sigma_{m,n} \in W^2(\bar{\rho})$. If $n = p - 1$, suppose that*

$$\bar{\rho}|_{I_{F_p}} \not\cong \begin{pmatrix} \omega^{m+e} & 0 \\ 0 & \omega^m \end{pmatrix}.$$

Then $\bar{\rho}$ is modular of weight $\sigma_{m,n}$.

Proof. If $\bar{\rho}|_{G_{F_p}}$ has a non-ordinary potentially Barsotti-Tate lift of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$, then by Corollary 7.3, $\bar{\rho}$ is modular of weight $\sigma_{m,n}$.

Suppose now that $\bar{\rho}|_{G_{F_p}}$ does not have a non-ordinary potentially Barsotti-Tate lift of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$. By Lemma 6.3, we must have

$$\bar{\rho}|_{I_{F_p}} \cong \begin{pmatrix} \omega^{m+n+e} & 0 \\ 0 & \omega^m \end{pmatrix}.$$

Furthermore, either $n + e \leq p - 1$, or $n = p - 1$. The second case is precisely the case excluded by the statement of this corollary.

Thus we must have $n + e \leq p - 1$. By Lemma 6.3, $\bar{\rho}|_{G_{F_p}}$ has a potentially Barsotti-Tate lift of type $\tilde{\omega}^{m+n} \oplus \tilde{\omega}^m$, so that by the assumption that $\bar{\rho}$ has an ordinary modular lift, Theorem 7.1, and Lemma 3.4, $\bar{\rho}$ is modular of weight $\sigma_{m,n}$ or $\sigma_{m+n,p-1-n}$. If $n = 0$ then we may conclude further that $\bar{\rho}$ is modular of weight $\sigma_{m,0}$. Assume for the sake of contradiction that $\bar{\rho}$ is not modular of weight $\sigma_{m,n}$ so we may now assume that $n \neq 0$, $n + e \leq p - 1$, and $\sigma_{m+n,p-1-n} \in W(\bar{\rho})$. In particular, by Corollary 5.6 we have $\sigma_{m+n,p-1-n} \in W^2(\bar{\rho})$, and we also know that $e < p - 1$ (because $e \leq p - 1 - n < p - 1$). Now, examining the definition of $W^2(\bar{\rho})$ (Definition 5.1), we see that we must have

$$\bar{\rho}|_{I_{F_p}} \cong \begin{pmatrix} \omega^{m+x} & 0 \\ 0 & \omega^{m+n+e-x} \end{pmatrix}$$

for some $1 \leq x \leq e$. Comparing with the expression above, we see that either $\omega^{m+x} = \omega^m$ or $\omega^{m+x} = \omega^{m+n+e}$. The first possibility requires $x \equiv 0 \pmod{p-1}$, a contradiction as $1 \leq x \leq e < p - 1$. The second requires $x \equiv n + e \pmod{p-1}$, which is a contradiction because $1 \leq x \leq e < n + e \leq p - 1$. The result follows. \square

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