ON A CONJECTURE OF SHIMURA CONCERNING PERIODS OF HILBERT MODULAR FORMS (Moduli spaces, Galois representations and L-functions)

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ON A CONJECTURE OF SHIMURA CONCERNING PERIODS OF HILBERT MODULAR FORMS

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Introduction. In this paper, we shall give an affirmative answer to an essential part of the conjecture of Shimura on $P$-invariants of Hilbert modular forms.

Let $F$ be a totally real algebraic number field of degree $n$ and $J_F$ be the set of all isomorphisms of $F$ into $\mathbb{C}$. Let $F_A$ (resp. $F_A^\infty$) be the adele ring (resp. the idele group) of $F$ and $F_A^\infty$ be the archimedean part of $F_A$. Let $\chi$ be a primitive system of eigenvalues of Hecke operators which occurs in the space of holomorphic Hilbert modular cusp forms on $GL(2,F_A)$ of weight $k$ and $f$ be the primitive form which belongs to $\chi$. In [S1], Shimura introduced an invariant $u(\epsilon,f) \in \mathbb{C}^x$ for every $\epsilon \in (\mathbb{Z}/2\mathbb{Z})^{J_F}$ such that

$$D(m,f,\varphi) \sim \pi^{mn}u(\epsilon,f)$$

for certain critical values $m \in \mathbb{Z}$ whenever a Hecke character $\varphi$ of $F_A$ satisfies $\varphi_\infty(x) = \prod_{\tau \in J_F} (\text{sgn } x_\tau)^{m+\epsilon(\tau)}$ for $x = (x_\tau) \in F_A^\infty$. Here $D(m,f,\varphi)$ is the standard $L$-function attached to $f$ twisted by $\varphi$ and we write $a \sim b$ for $a, b \in \mathbb{C}$ if $b \neq 0$ and $a/b \in \overline{\mathbb{Q}}$. Put $U(\chi,\epsilon) = u(\epsilon,f)$.

In [S4], Shimura introduced another invariant $Q(\chi,\delta) \in \mathbb{C}^x$ for every subset $\delta$ of $J_F$ when $\chi$ occurs in the space of holomorphic automorphic forms on a quaternion algebra over $\mathbb{F}$ of signature $(\delta,J_F\setminus \delta)$ and showed that this invariant appears in critical values of the Rankin-Selberg convolution of two Hilbert modular forms. He conjectured further the following (Conjecture 5.12 of [S4], cf. also [S5], p. 293, (C1), (C2), (C3), (C4) and (C9))

**Conjecture P.** Assume $k(\tau) \geq 2$ for all $\tau \in J_F$ and $k(\tau) \mod 2$ is independent of $\tau$. Put $k_0 = \max_{\tau \in J_F} k(\tau))$. Then for every subset $\delta$ of $J_F$ and every $\epsilon \in (\mathbb{Z}/2\mathbb{Z})^{\delta}$, there exists a constant $P(\chi,\delta,\epsilon) \in \mathbb{C}^x/\overline{\mathbb{Q}}^x$ which satisfies the following properties.

(P1) $\pi^{(k_0-2)n/2-\sum_{\tau \in J_F} k(\tau)/2} U(\chi,\epsilon) \sim P(\chi,J_F,\epsilon)$.

(P2) $Q(\chi,\delta) \sim \pi^{[G]} P(\chi,\delta,\epsilon_1)P(\chi,\delta,\epsilon_2)$ if $\epsilon_1(\tau) + \epsilon_2(\tau) \equiv 1 \mod 2$ for every $\tau \in \delta$.

(P3) $P(\chi,\delta_1 \cup \delta_2,\epsilon_1 \cup \epsilon_2) \sim P(\chi,\delta_1,\epsilon_1)P(\chi,\delta_2,\epsilon_2)$ if $\delta_1 \cap \delta_2 = \emptyset$, where

$$(\epsilon_1 \cup \epsilon_2)(\tau) = \begin{cases} \epsilon_1(\tau) & \text{if } \tau \in \delta_1, \\
\epsilon_2(\tau) & \text{if } \tau \in \delta_2. 
\end{cases}$$

(P4) When $\chi$ is of $CM$-type, $P(\chi,\delta,\epsilon) \sim \pi^{-[G]} p_K(\xi,\eta)$ holds, where $p_K$ stands for the symbol of $CM$-periods introduced in [S2].
The principal result of this paper is:

**Main Theorem.** Assume \( k(\tau) \geq 3 \) for all \( \tau \in J_F \) and \( k(\tau) \mod 2 \) is independent of \( \tau \). Then, for every \( \tau \in J_F \), there exist constants \( c^\pm(\chi) \in \mathbb{C}^x \) determined uniquely mod \( \overline{Q}^x \) such that

\[
U(\chi, \epsilon) \sim \prod_{\tau \in J_F} c^\epsilon(\tau)(\chi),
\]

\[
Q(\chi, \delta) \sim \pi^{n(1-k_0)+\sum_{\tau \in J_F} k(\tau)} \prod_{\tau \in \delta} c^+(\tau)c^-(\tau).
\]

Here we understand that \( c^0(\chi) = c^+(\chi) \), \( c^1(\chi) = c^-(\chi) \) identifying \( \mathbb{Z}/2\mathbb{Z} \) with \( \{0, 1\} \).

By this theorem, it is clear that \( P(\chi, \delta, \epsilon) \) satisfying \( (P1) \sim (P3) \) is given by

\[
P(\chi, \delta, \epsilon) \sim \pi^{(k_0-2)|\delta|/2} \pi^{-\sum_{\tau \in \delta} k(\tau)/2} \prod_{\tau \in \delta} c^\epsilon(\tau)(\chi).
\]

We note that in [Y], §6, we have defined \( Q(\chi, \delta) \mod \overline{Q}^x \) assuming only \( k(\tau) \geq 3 \) for all \( \tau \in \delta \).

Let us now outline our ideas of the proof and contents of each section. In §1, we shall review known properties of two basic period invariants \( Q(\chi, \delta) \) and \( U(\chi, \epsilon) \). In §2, Lemma 1, we shall show that a necessary and sufficient condition for the existence \( c^\pm(\chi) \) as in Main Theorem is the following relations \( (R1) \sim (R3) \).

\[
U(\chi, \epsilon_1)U(\chi, \epsilon_2) \sim \pi^{(k_0-1)|\delta|-\sum_{\tau \in \delta} k(\tau)} Q(\chi, J_F) \quad \text{if} \quad \epsilon_1(\tau) + \epsilon_2(\tau) \equiv 1 \mod 2 \quad \text{for every} \quad \tau.
\]

\[
Q(\chi, \delta_1)Q(\chi, \delta_2) \sim Q(\chi, \delta_1 \cup \delta_2) \quad \text{if} \quad \delta_1 \cap \delta_2 = \emptyset.
\]

\[
U(\chi, \epsilon_1)U(\chi, \epsilon_2) \sim U(\chi, \mu_1)U(\chi, \mu_2) \quad \text{if} \quad \{\epsilon_1(\tau), \epsilon_2(\tau)\} = \{\mu_1(\tau), \mu_2(\tau)\} \quad \text{for every} \quad \tau.
\]

We shall also prove \( (P4) \) in §2.

Now \( (R1) \) is already proved in [S1], Theorem 4.3. Harris [Ha3] proved \( (R2) \) under certain conditions, in particular when \( n, |\delta_1| \text{ and } |\delta_2| \) are all even. In §3, using a base change lift of \( \chi \) to a totally real quadratic extension of \( F \), we shall remove this parity condition and obtain \( (R2) \) (Theorem 2).

In §4, we shall prove \( (R3) \). By \( (0) \), we see that \( (R3) \) follows if

\[
D(m, f, \varphi_1)D(m, f, \varphi_2) \sim D(m, f, \psi_1)D(m, f, \psi_2)
\]
holds for one choice of a non-vanishing critical value $m$ and of Hecke characters $\varphi_1, \varphi_2, \psi_1, \psi_2$ of $F_A^\times$ whose infinity types correspond to $\epsilon_1, \epsilon_2, \mu_1, \mu_2$ respectively. Let $K$ be a quadratic extension of $F$ such that the Hecke character $\eta$ of $F_A^\times$ corresponding to $K/F$ satisfies $\eta_\infty = (\varphi_1 \varphi_2) = (\psi_1 \psi_2)$. Again by (0), (4) reduces to

\begin{equation}
D(m, \tilde{f}, \varphi_1 \circ N_{K/F}) \sim D(m, \tilde{f}, \psi_1 \circ N_{K/F}),
\end{equation}

where $\tilde{f}$ is the base change lift of $f$ to $K$. By our choice of $K$, $(\varphi_1 \circ N_{K/F})_\infty = (\psi_1 \circ N_{K/F})_\infty$ holds and we obtain (5) from a result of Hida [Hi] (§4, Theorem 3).

In §5, we shall prove the invariance of $c_\chi^\pm$ under the base change of $\chi$ to a totally real cyclic extension of $F$ (Theorem 4). In §6, we shall discuss a possible generalization of Main Theorem including the case where $k(\tau) = 2$ for some $\tau$.

Notation. Throughout the paper, we fix an algebraic closure $\overline{Q}$ of $Q$ as the subfield of $C$. A finite extension of $Q$ in $\overline{Q}$ will be called an algebraic number field. For an algebraic number field $F$, $F_v$ denotes the completion of $F$ at a place $v$, $J_F$ the set of all isomorphisms of $F$ into $C$ and $I_F$ the free abelian group generated by $J_F$. We denote by $\alpha_F^\ell$ (resp. $\alpha_F^p$) the set of all real (resp. complex) archimedean places of $F$ and put $\alpha_F^\ell = \alpha^\ell F \cup \alpha_F^p$. We shall drop the superscript $F$ when the reference to $F$ is clear from the context. When $F$ is totally real, we identify $\alpha_F^p$ with $J_F$; a totally imaginary quadratic extension of $F$ will be called a CM-extension of $F$.

For an algebraic group $G$ defined over $F$, $G_A$ denotes the adelization of $G$, $G_\infty$ the archimedean part of $G_A$ and $G_{\infty+}$ the identity component of $G_\infty$. For $x \in F_A^\times$, $|x|_A$ denotes the idele norm of $x$. For an irreducible automorphic representation $\pi = \otimes_v \pi_v$ of $GL(2, F_A)$, $L_f(s, \pi) = \prod_v L(s, \pi_v)$, $v$ extending over all finite places, denotes the finite part of the Jacquet-Langlands $L$-function attached to $\pi$. For $a, b \in C$, we denote $a \sim b$ if $b \neq 0$ and $a/b \in \overline{Q}$.

§1. Review on $Q$-invariants and $U$-invariants

Let $F$ be a totally real algebraic number field of degree $n$. Let $B$ be a quaternion algebra over $F$ such that $B$ splits (resp. ramifies) at the archimedean places $\tau \in \delta$ (resp. $\delta'$). We call such a $B$ a quaternion algebra of signature $(\delta, \delta')$. We assume $\delta \neq \emptyset$. Put $G = \text{Res}_{F/Q}(B^\times)$ and call $Z$ the center of $G$. We identify $Z_A$ with $F_A^\times$. For $k = \sum_{\tau \in \delta} k(\tau) \tau$ and $\kappa = \sum_{\tau \in \delta'} \kappa(\tau) \tau \in I_F$, we define the space of cusp forms $S_{k, \kappa}(B)$ on $G_A$ of weight $(k, \kappa)$ as in [S3], II, [Y], §6.

For $f, g \in S_{k, \kappa}(B)$, we define the inner product

\begin{equation}
\langle f, g \rangle = \int_{Z_{\infty+}G_Q \setminus G_A} f(x)^* g(x) \, dx
\end{equation}

normalizing the invariant measure so that $\text{vol}(Z_{\infty+}G_Q \setminus G_A) = 1$. If there exists $0 \neq f \in S_{k, \kappa}(B)$ and a Hecke character $\psi$ of $F_A^\times$ of finite order such that

\begin{equation}
f|T(p) = \chi(p)f \quad \text{for almost all} \quad p, \quad f(zx) = \psi(z)f(x), \quad z \in Z_A, \quad x \in G_A,
\end{equation}
$T(p)$ being the Hecke operator at the prime ideal $p$, we say that a system of eigenvalues of Hecke operators $\chi$ occurs in $S_{k,\kappa}(B)$. Strictly speaking, we should say that $(\chi, \psi)$ is a system of eigenvalues of Hecke operators. For simplicity, we shall drop $\psi$ and regard $\chi$ accompanying the central character $\psi$. Let $S_{k,\kappa}(B, \mathbb{Q})$ be the set of all $\mathbb{Q}$-rational elements in $S_{k,\kappa}(B)$. When $\chi$ is given, we set

$$W(\chi, B) = \{ f \in S_{k,\kappa}(B) \mid f|T(p) = \chi(p)f \text{ for almost all } p, \quad \text{ and } f(zx) = \psi(z)f(x), \quad z \in Z_A, x \in G_A \},$$

$$W(\chi, B, \overline{\mathbb{Q}}) = W(\chi, B) \cap S_{k,\kappa}(B).$$

By the Shimizu-Jacquet-Langlands correspondence ([JL]), if $\chi$ occurs in $S_{k,\kappa}(B)$, then it also occurs in $S_{m,0}(M_2(F))$, where $m(\tau) = k(\tau)$ (resp. $\kappa(\tau) + 2$) if $\tau \in \delta$ (resp. $\tau \in \delta'$). If (1.2) holds for all $p$ with the primitive form (the new form) $f \in S_{m,0}(M_2(F))$, then we call $\chi$ primitive (cf. [S3], II, p. 583).

Assume that $\chi$ occurs in $S_{k,0}(M_2(F))$. In [Y], §6, we have shown the following facts sharpening previous results obtained by Shimura [S4], [S5].

(1.3) $\langle f, f \rangle \mod \overline{\mathbb{Q}}^\times$ is independent of $0 \neq f \in W(\chi, B, \overline{\mathbb{Q}})$.

(1.4) If $B_1$ and $B_2$ are of signature $(\delta, \delta')$ and $k(\tau) \geq 2$ for all $\tau \in J_F$, then $\langle f, f \rangle \sim \langle g, g \rangle$ for $f \in W(\chi, B_1, \overline{\mathbb{Q}})$, $0 \neq g \in W(\chi, B_2, \overline{\mathbb{Q}})$.

If $W(\chi, B) \neq \{0\}$ for some quaternion algebra $B$ of signature $(\delta, \delta')$, we put

(1.5) $Q(\chi, \delta) = \langle f, f \rangle$

taking some non-zero form $f \in W(\chi, B, \overline{\mathbb{Q}})$. By (1.3) and (1.4), $Q(\chi, \delta) \in \mathbb{C}^\times/\overline{\mathbb{Q}}^\times$ is well defined. Let $F_1$ be a totally real cyclic extension of degree $l$ of $F$. We exclude the case where $k(\tau) = 1$ for all $\tau \in J_F$. Then there exists a base change lift $\tilde{\chi}$ of $\chi$ which occurs in $S_{k,0}(M_2(F_1))$ where $\tilde{k}(\tau) = k(\tau|F_1)$, $\tau \in J_{F_1}$. We have

(1.6) If $\chi$ occurs in $S_{m,\kappa}(B)$, then $\tilde{\chi}$ occurs in $S_{\tilde{m},\tilde{\kappa}}(B \otimes_F F_1)$.

(1.7) $Q(\tilde{\chi}, \tilde{\delta}) = Q(\chi, \delta)^{1/l}$ if $k(\tau) \geq 3$ for all $\tau \in \delta$.

Here we have assumed $k(\tau) \geq 3$ for all $\tau \in \delta$ for some technical reasons (cf. §6); $\tilde{m}(\tau) = m(\tau|J_{F_1})$, $\tilde{k}(\tau) = k(\tau|J_{F_1})$, $\tau \in J_{F_1}$ and $\tilde{\delta}$ is the full inverse image of $\delta$ under the restriction map $J_{F_1} \longrightarrow J_F$. We can use (1.7) to define $Q(\chi, \delta)$ when $\chi$ does not occur in any $B$ of signature $(\delta, \delta')$. In other words, we can find $F_1$ and $B_1$ of signature $(\tilde{\delta}, \tilde{\delta}')$ such that $\tilde{\chi}$ occurs in $S_{\tilde{m},\tilde{\kappa}}(B_1)$ and put $Q(\chi, \delta) = Q(\tilde{\chi}, \tilde{\delta})^{1/l}$. Then $Q(\chi, \delta) \in \mathbb{C}^\times/\overline{\mathbb{Q}}^\times$ is well defined and (1.7) holds for this definition. We set $Q(\chi, \emptyset) = 1 \in \mathbb{C}^\times/\overline{\mathbb{Q}}^\times$. 
Let $\chi$ be a primitive system of eigenvalues of Hecke operators which occurs in $S_{k,0}(M_{2}(F))$. Put

\begin{equation}
(1.8) \quad k_{0} = \max_{\tau \in J_{F}}(k(\tau)), \quad k^{0} = \min_{\tau \in J_{F}}(k(\tau)).
\end{equation}

Let $f \in W(\chi, M_{2}(F))$ be the primitive form. We attach a Dirichlet series $D(s, f) = \sum_{m} C(m, f) N(m)^{-s}$ by \cite{Sl}.

Let $f \in W(\chi, M_{2}(F))$ be the primitive form. We attach a Dirichlet series $D(s, f, \varphi)$ where $\varphi_{*}$ denotes the ideal character associated to $\varphi$ and $m$ extends over all integral ideals of $F$.

\begin{equation}
D(s, f, \varphi) = \sum_{m} C(m, f) \varphi_{*}(m) N(m)^{-s}
\end{equation}

where $\varphi_{*}$ denotes the ideal character associated to $\varphi$ and $m$ extends over all integral ideals of $F$. Set $L(s, \chi, \varphi) = \sum_{\mathfrak{m}} \chi(\mathfrak{m}) \varphi_{*}(\mathfrak{m}) N(\mathfrak{m})^{-s}$.

Then we have $L(s, \chi, \varphi) = D(s + \frac{k_{0}}{2} - 1, f, \varphi)$.

In \cite{Sl}, Theorem 4.3, Shimura obtained the following result (cf. also Rohrlich \cite{R}) which we shall recall in a crude form sufficient for our present purpose.

**Theorem S.** Assume $k(\tau) \geq 2$ for all $\tau \in J_{F}$ and $k(\tau) \mod 2$ is independent of $\tau$. For every $\epsilon = (\epsilon(\tau)) \in (\mathbb{Z}/2\mathbb{Z})^{J_{F}}$, there exists a constant $u(\epsilon, f) \in \mathbb{C}^{\times}/\overline{\mathbb{Q}}^{\times}$ with the following properties.

(I) If $\varphi$ is a Hecke character of $F_{A}^{\times}$ such that

$$
\varphi_{\infty}(x) = \prod_{\tau \in J_{F}} \text{sgn}(x_{\tau})^{\epsilon(\tau) + m}, \quad x = (x_{\tau}) \in F_{\infty}^{\times},
$$

then

$$
D(m, f, \varphi) \sim \pi^{mn} u(\epsilon, f)
$$

for every integer $m$ such that

$$
\frac{k_{0} - k^{0}}{2} < m < \frac{k_{0} + k^{0}}{2}.
$$

(II) If $\epsilon_{1}, \epsilon_{2} \in (\mathbb{Z}/2\mathbb{Z})^{J_{F}}$ satisfy $\epsilon_{1}(\tau) + \epsilon_{2}(\tau) \equiv 1 \mod 2$ for all $\tau$, then

$$
u(\epsilon_{1}, f) u(\epsilon_{2}, f) \sim \pi^{n(1-k_{0})+\sum_{\tau \in J_{F}} k(\tau)} \langle f, f \rangle.
$$

Put $U(\chi, \epsilon) = u(\epsilon, f)$ taking the primitive form $f \in W(\chi, M_{2}(F))$.

Remark. Let $f$ be as above and let $\pi = \otimes_{v} \pi_{v}$ be the irreducible automorphic representation of $GL(2, F_{A})$ generated by $f$. Then $\pi$ is unitary.

(1) By somewhat laborious computations taking a suitable model of a local component $\pi_{v}$ of $\pi$ and letting the Hecke operator at $v$ defined in \cite{Sl}, §2 act on the new vector, we can verify the exact equality $D(s, f) = L_{f}(s - \frac{k_{0}-1}{2}, \pi)$. However this is not necessarily so for $D(s, f, \varphi)$ and $L_{f}(s - \frac{k_{0}-1}{2}, \pi \otimes \varphi)$. In fact, some finitely many Euler factors of $L_{f}(s - \frac{k_{0}-1}{2}, \pi \otimes \varphi)$ may not appear in $D(s, f, \varphi)$. The condition for the exact coincidence
is \( L(s, \varphi_v \otimes \varphi_v) = 1 \) whenever \( \varphi \) ramifies at \( v \). This condition is satisfied at \( v \) if the exponent of the conductor of \( \varphi_v \) is greater than the exponent of the conductor of \( \pi_v \).

(2) Let \( \psi \) be a Hecke character of \( F^\times_A \) such that

\[
\psi_\infty(x) = \prod_{\tau \in J_F} \text{sgn}(x_{\tau})^{\epsilon_1(\tau)}, \quad x = (x_\tau) \in F^\times_\infty.
\]

Let \( f_\psi \) be the primitive form which belongs to \( \pi \otimes \psi \).

We have

\[
(1.9) \quad u(\epsilon, f_\psi) \sim u(\epsilon + \epsilon_1, f)
\]

for every \( \epsilon \in (Z/2Z)^{J_F} \).

To see this, first choose a critical value \( m \). Take a Hecke character \( \varphi \) of \( F^\times_A \) so that \( \varphi_\infty \) is given by the formula in Theorem S, (1) and that the conductor of \( \varphi \) is divisible by \( p^{e+1} \) whenever \( p^e \) divides one of the conductors of \( \pi, \pi \otimes \psi, \psi \). Then we have

\[
D(s, f_\psi, \varphi) = D(s, f, \psi \varphi) = L_f(s - \frac{k_0 - 1}{2}, \pi \otimes \psi \varphi).
\]

By a theorem of Rohrlich, we can further impose the condition on \( \varphi \) that \( L_f(s, \pi \otimes \psi) \neq 0 \) for \( s = m - \frac{k_0 - 1}{2} \). Then (1.9) follows from Theorem S. As a result, we see that

\[
(1.10) \quad L_f(m - \frac{k_0 - 1}{2}, \pi \otimes \varphi) \sim \pi^{mn} u(\epsilon, f)
\]

for a Hecke character \( \varphi \) and critical values \( m \) as in Theorem S.

(3) It can be shown, using the unitarity of \( \pi_v \), that \( D(s, f, \psi) = L_f(s - \frac{k_0 - 1}{2}, \pi \otimes \varphi) \) is an entire function which has no zeros for \( \Re(s) \geq k_0/2 \). We can give another proof of (1.9) and (1.10) using this fact and the functional equation of \( L(s, \pi \otimes \varphi) \).

§2. Preliminary reduction of Conjecture P

Our main theorem states that \( 2^{n+1} \) quantities \( U(\chi, \epsilon) \) and \( Q(\chi, \delta) \) can be given by \( 2n \) quantities \( c^\pm_\chi(\chi) \), which implies some highly non-trivial relations among \( U(\chi, \epsilon) \) and \( Q(\chi, \delta) \). We shall analyze these relations by the next Lemma.

Lemma 1. Let \( J = \{1, 2, \cdots, n\} \) and let \( \Lambda_n \) be the set of all mappings from \( J \) to \( \{\pm 1\} \). Assume that for every \( \epsilon \in \Lambda_n \) and every subset \( I \) of \( J \), there are given quantities \( p(\epsilon) \in \mathbb{C}^\times/\overline{Q}^\times \) and \( q(I) \in \mathbb{C}^\times/\overline{Q}^\times \) which satisfy the following properties:

\[
(R1) \quad p(\epsilon)p(-\epsilon) = q(J) \quad \text{where} \quad (-\epsilon)(i) = -\epsilon(i), \quad i \in J.
\]

\[
(R2) \quad q(I_1 \cup I_2) = q(I_1)q(I_2) \quad \text{if} \quad I_1 \cap I_2 = \emptyset.
\]

\[
(R3) \quad p(\epsilon_1)p(\epsilon_2) = p(\mu_1)p(\mu_2) \quad \text{if} \quad \{\epsilon_1(i), \epsilon_2(i)\} = \{\mu_1(i), \mu_2(i)\} \quad \text{for every} \quad 1 \leq i \leq n.
\]
Then there exist $2n$ constants $c_i^\pm \in \mathbb{C}^\times/\overline\mathbb{Q}^\times$, $1 \leq i \leq n$ such that
\begin{align}
(2.1) \quad p(\epsilon) &= \prod_{i=1}^{n} c_i^{\epsilon(i)}, \quad \epsilon \in \Lambda_n, \\
(2.2) \quad q(I) &= \prod_{i \in I} c_i^+ c_i^-, \quad \text{if } I \subseteq J.
\end{align}
Moreover $c_i^\pm \in \mathbb{C}^\times/\overline\mathbb{Q}^\times$, $1 \leq i \leq n$ are unique. In (2.1) and (2.2), we understand that $c_1^+ = c_i^+, c_i^- = c_i^-$, $\prod_{i \in \emptyset} c_i^+ c_i^- = 1$.

Proof. By (R2), we have $q(\emptyset) = 1$. Hence (2.2) for $I = \emptyset$ holds. If $n = 1$, the assertion holds with
\[ c_1^+ = p(\epsilon), \quad c_1^- = p(-\epsilon) \quad \text{for } \epsilon : 1 \rightarrow 1. \]
Now we assume $n \geq 2$ and that the assertion holds up to $n - 1$. Let $J' = \{1, 2, \cdots, n - 1\} = J \setminus \{n\}$ and let $\Lambda_{n-1}$ be the set of all mappings from $J'$ to $\{-1, 1\}$. Define $\omega, \omega' \in \Lambda_n$ by
\begin{align*}
\omega_+ & : \{1, 2, \cdots, n-1, n\} \rightarrow \{1, 1, \cdots, 1, 1\}, \\
\omega'_+ & : \{1, 2, \cdots, n-1, n\} \rightarrow \{-1, -1, \cdots, -1, 1\}, \\
\omega_- & : \{1, 2, \cdots, n-1, n\} \rightarrow \{1, 1, \cdots, 1, -1\}, \\
\omega'_- & : \{1, 2, \cdots, n-1, n\} \rightarrow \{-1, -1, \cdots, -1, -1\}.
\end{align*}
By (R1), we have
\begin{equation}
(2.3) \quad p(\omega_+) p(\omega_-) = p(\omega'_+) p(\omega'_-) = q(J).
\end{equation}
For a given $\epsilon \in \Lambda_{n-1}$, choose an extension $\epsilon^* \in \Lambda_n$ so that $\epsilon^*(i) = \epsilon(i)$, $1 \leq i \leq n - 1$ and set
\begin{equation}
(2.4) \quad p'(\epsilon) = p(\epsilon^*) / \sqrt{p(\omega_{\epsilon^*(n)}) p(\omega'_{\epsilon^*(n)}) / q(J')} \in \mathbb{C}^\times/\overline\mathbb{Q}^\times.
\end{equation}
By (R3), we see that $p'(\epsilon)$ does not depend on the choice of $\epsilon^*$. For $I' \subseteq J'$, we set
\begin{equation}
(2.5) \quad q'(I') = q(I').
\end{equation}
Then we can verify that the quantities $p'(\epsilon), \epsilon \in \Lambda_{n-1}$ and $q'(I')$ satisfy
\begin{align}
(R'1) \quad p'(\epsilon) p'(-\epsilon) &= q'(J'), \\
(R'2) \quad q'(I_1' \cup I_2') &= q'(I_1') q'(I_2') \quad \text{if } I_1' \cap I_2' = \emptyset.
\end{align}
\[
R'(3) \quad p'(\epsilon_1)p'(\epsilon_2) = p'(\mu_1)p'(\mu_2) \quad \text{if} \quad \{\epsilon_1(i), \epsilon_2(i)\} = \{\mu_1(i), \mu_2(i)\}
\]

for every \(1 \leq i \leq n - 1\).

Relation \(R'(2)\) is trivial. To see \(R'(1)\), we may choose an extension \(\epsilon^*\) of \(\epsilon\) so that \(\epsilon^*(n) = 1\) and may apply (2.4). Then we have

\[
p'(\epsilon)p'(-\epsilon) = p(\epsilon^*)/\sqrt{p(\omega_+)}p(\omega_+)/q(J') \cdot p(-\epsilon^*)/\sqrt{p(\omega_-)}p(\omega_-)/q(J')
\]

by (2.3) and \(R1\). Similarly \(R'(3)\) follows from \(R3\).

By the hypothesis of induction, there exist \(2(n-1)\) quantities \(c^\pm_i \in \mathbb{C}^\times/\overline{Q}^\times\), \(1 \leq i \leq n-1\) such that

\[
p'(\epsilon) = \prod_{i=1}^{n-1} c^{\epsilon(i)}_i, \quad \epsilon \in \Lambda_{n-1}, \tag{2.6}
\]

\[
q(I') = q'(I') = \prod_{i \in I'} c_i^+ c_i^- \quad \text{if} \quad I' \subseteq J'. \tag{2.7}
\]

Set

\[
c_n^+ = \sqrt{p(\omega_+)}p(\omega_+)/q(J'), \quad c_n^- = \sqrt{p(\omega_-)}p(\omega_-)/q(J'). \tag{2.8}
\]

To see the relation (2.1), put \(\epsilon = \epsilon^*|J\) for \(\epsilon^* \in \Lambda_n\). By (2.4), (2.6) and (2.8), we have

\[
p(\epsilon^*) = p'(\epsilon)\sqrt{p(\omega_{\epsilon^*(n)})p(\omega'_{\epsilon^*(n)})/q(J')} = \left(\prod_{i=1}^{n-1} c_i^{\epsilon(i)}\right)c_n^{\epsilon^*(n)} = \prod_{i=1}^{n} c_i^{\epsilon^*(i)}.
\]

Hence (2.1) is satisfied.

To see (2.2), we may assume \(I \ni n\). Put \(I' = I \setminus \{n\}\). By (2.8), (2.3) and \(R2\), we get

\[
c_n^+ c_n^- = q(J)/q(J') = q(\{n\}).
\]

Then we obtain

\[
q(I) = q(I')q(\{n\}) = \left(\prod_{i \in I'} c_i^+ c_i^-\right)c_n^+ c_n^- = \prod_{i \in I} c_i^+ c_i^-
\]

by \(R2\).

The uniqueness of \(c_i^\pm\) is clear since we can express \(c_i^\pm\) by a formula similar to (2.8) if (2.1) and (2.2) hold. This completes the proof.

Identify \(J_F\) with \(\{1,2, \cdots, n\}\) and \(\mathbb{Z}/2\mathbb{Z}\) with \(\{1,-1\}\). By the above Lemma, we see that our Main Theorem is reduced to \(R1 \sim R3\) given in the introduction. We note that \(R1\) follows from Theorem S, (II) in view of the definition of \(Q(\chi, J_F)\).
In the rest of this section, we shall prove (P4). Let $K$ be a $CM$-extension of $F$. For $\alpha, \beta \in I_K$, let $p_K(\alpha, \beta) \in \mathbb{C}^x/\overline{\mathbb{Q}}^x$ denote the $CM$-period defined in [S2]. Let $\Phi$ be a $CM$-type of $K$ and set $\xi = \sum_{\tau \in \Phi} \xi_{\tau} \cdot \tau \in I_K$, $\xi_{\tau} \geq 0$ for all $\tau$. Let $\Xi$ be a primitive Hecke character of the ideal group of $K$ with conductor $c$ such that

$$\Xi((a)) = a^\xi/|a^\xi|$$

if $a \in K$, $a \equiv 1 \mod c$.

Assume $\xi_{\tau} > 0$ for some $\tau$. Then there exists a primitive system of eigenvalues of Hecke operators $\chi$ occurring in $S_{k,0}(M_2(F))$ such that

$$L(s, \chi) = L(s - 1/2, \Xi)$$

where $k(\tau|F) = \xi_{\tau} + 1$, $\tau \in \Phi$. If $\xi_{\tau} \mod 2$ is independent of $\tau$ and $\xi_{\tau} > 0$ for all $\tau$, then we have

$$U(\chi, \epsilon) \sim \pi^{(\sum_{\tau \in J_F} k(\tau) - n\tau_0)/2} p_K(\xi, \Phi)$$

by [S4], Theorem 5.11, (iii). On the other hand, we have

$$Q(\chi, \delta) \sim \pi^{-|\delta|} p_K(\xi, 2\eta)$$

by [S4], Theorem 5.8, where $\eta$ is the subset of $\Phi$ such that $\text{Res}_{K/F}(\eta) = \delta$. Now for such a $\chi$, (R2) follows from the bilinearity of $p_K$ (cf. [S2], Theorem 1.1) and (R3) is trivially satisfied. We see that the solution to (1) and (2) in the introduction is given by

$$(2.12) \quad c_\tau^+(\chi) = c_\tau^-(\chi) = \pi^{(k(\tau) - k_0)/2} p_K(\xi, \tilde{\tau}) \quad \tau \in J_F$$

from the bilinearity of $p_K$, where $\tilde{\tau} \in \Phi$ denotes the element such that $\tilde{\tau}|F = \tau$. By (3) in the introduction, we have

$$(2.13) \quad P(\chi, \delta, \epsilon) \sim \pi^{-|\delta|} p_K(\xi, \eta) \quad \text{for every } \epsilon \in (\mathbb{Z}/2\mathbb{Z})^\delta,$$

which is consistent with (C9) of [S5].

§3. Verification of (R2)

We shall use the following result of Harris (cf. [Ha3], §2.6).

**Theorem HA.** Let $\chi$ be a primitive system of eigenvalues of Hecke operators which occurs in $S_{k,0}(M_2(F))$. Assume $k(\tau) \geq 2$ for all $\tau \in J_F$ and $k(\tau) \mod 2$ is independent of $\tau$. Let $\alpha$ and $\beta$ be subsets of $J_F$ such that $\alpha \cap \beta = \emptyset$. If $n$, $|\alpha|$ and $|\beta|$ are all even, then

$$Q(\chi, \alpha \cup \beta) \sim Q(\chi, \alpha)Q(\chi, \beta).$$

By a base change argument, we can remove the parity condition in Theorem HA when $k(\tau) \geq 3$ for all $\tau \in \alpha \cup \beta$. 

**Theorem 2.** Let $\alpha$ and $\beta$ be subsets of $J_F$ such that $\alpha \cap \beta = \emptyset$. Assume that $k(\tau) \geq 2$ for all $\tau \in J_F$, $k(\tau) \geq 3$ for all $\tau \in \alpha \cup \beta$ and that $k(\tau) \mod 2$ is independent of $\tau$. Then we have

$$Q(\chi, \alpha \cup \beta) \sim Q(\chi, \alpha)Q(\chi, \beta).$$

**Proof.** Let $F_1$ be a totally real quadratic extension of $F$. Let $\tilde{\alpha}$ and $\tilde{\beta}$ be the full inverse images of $\alpha$ and $\beta$ under the restriction map $J_{F_1} \rightarrow J_F$ respectively. Let $\tilde{\chi}$ be a base change lift of $\chi$ which occurs in $S_{k,0}(M_2(F_1))$, where $\tilde{k}(\tau) = k(\tau|J_F)$, $\tau \in J_{F_1}$. We can apply Theorem HA to $\tilde{\chi}$, $\tilde{\alpha}$, $\tilde{\beta}$ and obtain

$$Q(\tilde{\chi}, \tilde{\alpha} \cup \tilde{\beta}) \sim Q(\tilde{\chi}, \tilde{\alpha})Q(\tilde{\chi}, \tilde{\beta}).$$

By (1.7), we have

$$Q(\chi, \alpha \cup \beta)^2 \sim Q(\chi, \alpha)^2Q(\chi, \beta)^2.$$

Hence the assertion follows.

By Theorem 2, the condition (R2) is verified.

---

§4. Verification of (R3)

To present our arguments in a clear-cut way, let us first recall a few facts on representation theory of $GL(2, L)$ for an archimedean field $L$. Let $\mathcal{H}_L$ denote the Hecke algebra of $GL(2, L)$ defined in Jacquet-Langlands [JL], p. 153, p. 220.

First let $L = \mathbb{R}$. For a positive integer $p$, let

$$\mu_1(t) = |t|^{p/2}, \quad \mu_2(t) = |t|^{-p/2} \text{sgn}(t)^{\epsilon(p)}, \quad t \in \mathbb{R}^\times$$

where $\epsilon(p) = 0$ or 1 according as $p$ is odd or even. Consider the representation $\sigma_p = \sigma(\mu_1, \mu_2)$ described in [JL], Theorem 5.11. Then $\sigma_p$ is a unitary discrete series representation of $\mathcal{H}_L$. If an irreducible automorphic representation $\pi = \otimes_v \pi_v$ of $GL(2, F_A)$ is generated by $f \in S_{k,0}(M_2(F))$, then we have

$$\pi_\infty = \otimes_{\tau \in J_F} \sigma_{k(\tau)-1}$$

if $k(\tau) \geq 2$ for all $\tau \in J_F$. Let $\omega_p$ be the character of $\mathbb{C}^\times$ given by

$$\omega_p(z) = z^p(z\overline{z})^{-p/2}, \quad z \in \mathbb{C}^\times.$$

Then we have

$$\sigma_p = \pi(\omega_p)$$

in the notation of [JL], p. 176–181. We also have

$$L(s, \sigma_p) = L(s, \omega_p) = 2(2\pi)^{-s+(s+p/2)}\Gamma(s+\frac{p}{2}).$$

(4.1)

Let $L = \mathbb{C}$. For two quasi-characters $\mu_1$, $\mu_2$ of $\mathbb{C}^\times$, let $\pi(\mu_1, \mu_2)$ be the representation of $\mathcal{H}_L$ described in [JL], Theorem 6.2.

Now let $W_C = \mathbb{C}^\times$, $W_R = W_{R,C}$ be the Weil groups. We may write (4.1) as $\sigma_p = \pi(\text{Ind}_{W_C}^R \omega_p)$ in terms of the Langlands parametrization. Hence the base change lift of $\sigma_p$ to $\mathcal{H}_C$ is given by $\pi(\text{Ind}_{W_C}^R \omega_p)(W_C) = \pi(\omega_p, \tilde{\omega}_p)$ by Langlands [L], p.16, e).

We quote Hida [Hi], Theorem 8.1 in a crude form sufficient for our present purpose.
Theorem HI. Let $K$ be an algebraic number field. Let $\pi = \otimes_{w} \pi_{w}$ be an irreducible unitary cuspidal automorphic representation of $GL(2, K_{A})$. Assume that

$$\pi_{\infty} = \otimes_{\tau \in a_{r}} \pi_{\tau}$$

with $k(\tau) \geq 2$ for all $\tau \in a$ and $k(\tau) \mod 2$ is independent of $\tau$. Put $k_{0} = \max_{\tau \in a} k(\tau)$. Then for every $\epsilon \in (\mathbb{Z}/2\mathbb{Z})^{a_{r}}$, there exists a constant $U(\pi, \epsilon) \in C^{x}$ which satisfies the following properties. If $\varphi$ is a Hecke character of $K_{A}^{x}$ of finite order such that

$$\varphi_{\infty}(x) = \prod_{\tau \in a_{r}} \text{sgn}(x_{\tau})^{\epsilon(\tau)+m}, \quad x = (x_{\tau})_{\tau \in a} \in K_{\infty}^{x},$$

then

$$L_{f}(m - \frac{k_{0} - 1}{2}, \pi) \sim \pi^{m[K:Q]} U(\pi, \epsilon)$$

for every integer $m$ such that

$$\frac{k_{0} - k(\tau)}{2} < m < \frac{k_{0} + k(\tau)}{2} \quad \text{for every} \quad \tau \in a.$$

We are going to verify (R3) using this theorem. It suffices to show

Theorem 3. Let $f \in S_{k,0}(M_{2}(F))$ be a primitive cusp form. We assume $k(\tau) \geq 3$ for all $\tau \in J_{F}$ and $k(\tau) \mod 2$ is independent of $\tau$. Then we have

$$(4.3) \quad u(\epsilon_{1}, f)u(\epsilon_{2}, f) \sim u(\mu_{1}, f)u(\mu_{1}, f)$$

whenever $\epsilon_{1}, \epsilon_{2}, \mu_{1}, \mu_{2} \in (\mathbb{Z}/2\mathbb{Z})^{J_{F}}$ satisfy

$$(4.4) \quad \{\epsilon_{1}(\tau), \epsilon_{2}(\tau)\} = \{\mu_{1}(\tau), \mu_{2}(\tau)\} \quad \text{for all} \quad \tau \in J_{F}.$$  

Proof. We choose an integer $m$ which satisfies the condition of Theorem S, (I). Since we have assumed $k^{0} \geq 3$, we can choose such an $m$ so that $m \geq (k_{0} + 1)/2$. We fix and denote it by $m_{0}$. Then we have $D(m_{0}, f, \varphi) \neq 0$ for every Hecke character $\varphi$ of $F_{A}^{x}$ of finite order (cf. [S1], Prop. 4.16). Let $\varphi_{1}, \varphi_{2}, \psi_{1}, \psi_{2}$ be Hecke characters of $F_{A}^{x}$ of finite order such that

$$(\varphi_{i})_{\infty}(x) = \prod_{\tau \in J_{F}} (\text{sgn}(x_{\tau}))^{\epsilon_{i}(\tau)+m_{0}}, \quad i = 1, 2,$$

$$(\psi_{i})_{\infty}(x) = \prod_{\tau \in J_{F}} (\text{sgn}(x_{\tau}))^{\mu_{i}(\tau)+m_{0}}, \quad i = 1, 2,$$

for $x = (x_{\tau}) \in F_{\infty}^{x}$. By Theorem S, (I), (4.3) reduces to

$$(4.6) \quad D(m_{0}, f, \varphi_{1})D(m_{0}, f, \varphi_{2}) \sim D(m_{0}, f, \psi_{1})D(m_{0}, f, \psi_{2}).$$
By (4.4), we have $(\varphi_1\varphi_2)_\infty = (\psi_1\psi_2)_\infty$. If $(\varphi_1\varphi_2)_\infty$ is trivial, then we have $\epsilon_1 = \epsilon_2 = \mu_1 = \mu_2$ by (4.4); hence (4.3) holds. We may assume that $(\varphi_1\varphi_2)_\infty$ is non-trivial. Choose $a \in F$ so that $\tau(a) > 0$ (resp. $\tau(a) < 0$) if $(\varphi_1\varphi_2)_\infty$ is trivial (resp. non-trivial). Set $K = F(\sqrt{a})$. Then $K$ is a quadratic extension of $F$. Let $\eta_K$ be the Hecke character of $F_A^\times$ which corresponds to the extension $K/F$. By the choice of $a$, we have $(\eta_K)_\infty = (\varphi_1\varphi_2)_\infty$.

Let $\pi = \otimes_v \pi_v$ be the irreducible automorphic representation of $GL(2, F_A)$ generated by $\mathfrak{f}$ and $\tilde{\pi} = \otimes_w \tilde{\pi}_w$ be the base change lift of $\pi$ to $GL(2, K_A)$. Then we have

$$L(s, \tilde{\pi}) = L(s, \pi)L(s, \pi \otimes \eta_K), \quad L_f(s, \tilde{\pi}) = L_f(s, \pi)L_f(s, \pi \otimes \eta_K),$$

(4.7)

$$\pi_\infty = \otimes_{\tau \in J_F} \sigma_k(\tau^{-1}),$$

$$\tilde{\pi}_\infty = \otimes_{\tau \in a_c} \pi(\omega_k, \overline{\omega}_k - 1).$$

Since the base change lift of $\pi \otimes \varphi_1$ to $K$ is $\tilde{\pi} \otimes (\varphi_1 \circ N_{K/F})$, we have

$$L_f(s, \tilde{\pi} \otimes (\varphi_1 \circ N_{K/F})) = L_f(s, \pi \otimes \varphi_1)L_f(s, \pi \otimes \varphi_1 \eta_K).$$

We have $D(m_0, \mathfrak{f}, \varphi) \sim L_f(m_0 - \frac{k_0 - 1}{2}, \pi \otimes \varphi)$ for every Hecke character $\varphi$ of $F_A^\times$ of finite order. Since $(\varphi_1\eta_K)_\infty = (\varphi_2)_\infty$, we have $L_f(m_0 - \frac{k_0 - 1}{2}, \pi \otimes \varphi_1\eta_K) \sim L_f(m_0 - \frac{k_0 - 1}{2}, \pi \otimes \varphi_2)$ by Theorem S, (I). Therefore (4.6) reduces to

(4.8)

$$L_f(m_0 - \frac{k_0 - 1}{2}, \pi \otimes (\varphi_1 \circ N_{K/F})) \sim L_f(m_0 - \frac{k_0 - 1}{2}, \tilde{\pi} \otimes (\psi_1 \circ N_{K/F})).$$

Assume $\tau \in J_F$ is unramified in $K$. Then $(\varphi_1\varphi_2)_\infty = (\psi_1\psi_2)_\infty = 1$ and we see that \{\epsilon_1(\tau), \epsilon_2(\tau)\} and \{\mu_1(\tau), \mu_2(\tau)\} are either \{0, 0\} or \{1, 1\}. By (4.4), we get $\epsilon_1(\tau) = \mu_1(\tau)$, $(\varphi_1)_\infty = (\psi_1)_\infty$. Therefore we obtain

$$(\varphi_1 \circ N_{K/F})_\infty = (\psi_1 \circ N_{K/F})_\infty.$$
We have $\overline{\pi} \cong \pi \otimes \psi^{-1}$. By definition, it is obvious that $Q(\chi, \delta) \sim \overline{Q(\chi, \delta)}$ for every $\delta \subset J_F$.

Since $\overline{\chi} = \chi \otimes \psi^{-1}$, we have (cf. [Y], Prop. 6.5)

\[(4.10) \quad Q(\overline{\chi}, \delta) \sim \overline{Q(\chi, \delta)}.\]

As in Theorem S, choose a critical value $m$ and a Hecke character $\varphi$ of $F_A^\chi$ of finite order for $\epsilon \in (\mathbb{Z}/2\mathbb{Z})^J$ so that $L_f(m - \frac{k_0-1}{2}, \pi \otimes \varphi) \neq 0$. By Theorem S, we have

\[\pi^{mn}U(\chi, \epsilon) \sim L_f(m - \frac{k_0-1}{2}, \pi \otimes \varphi) \sim \pi^{mn}U(\overline{\chi}, \epsilon)\]

Hence we get

\[(4.11) \quad U(\overline{\chi}, \epsilon) \sim \overline{U(\chi, \epsilon)}.\]

By (4.10), (4.11) and Lemma 2.1, we obtain (4.9) (cf. [S5], p. 293, (C2)).

§5. The invariance of $c^\pm_\tau(\chi)$ under a base change

**Theorem 4.** Let $F_1$ be a totally real cyclic extension of $F$. Let $\chi$ be a primitive system of eigenvalues of Hecke operators which occurs in $S_{k,0}(M_2(F))$. We assume that $k(\tau) \geq 3$ for all $\tau \in J_F$ and that $k(\tau) \mod 2$ is independent of $\tau$. Let $\tilde{\chi}$ be the base change lift of $\chi$ such that $\tilde{\chi}$ occurs in $S_{\tilde{k},0}(M_2(F_1))$ and that $\tilde{\chi}$ is primitive, where $\tilde{k}(\tau) = k(\tau|F)$, $\tau \in J_{F_1}$. Then we have

\[(5.1) \quad c^\pm_\tau(\tilde{\chi}) = c^\pm_\tau|F(\chi) \quad \text{for every} \quad \tau \in J_{F_1}.\]

**Proof.** Let $\tilde{f} \in W(\tilde{\chi}, M_2(F_1), \overline{Q})$ and $f \in W(\chi, M_2(F), \overline{Q})$ be primitive forms. Let $\tilde{\pi}$ (resp. $\pi$) be the irreducible automorphic representation of $GL(2, (F_1)_A)$ (resp. $GL(2, F_A)$) generated by $\tilde{f}$ (resp. $f$). Then we have

\[(5.2) \quad L_f(s, \pi \otimes \varphi^\sigma) = L_f(s, \tilde{\pi} \otimes \varphi)\]

for every $\sigma \in \text{Gal}(F_1/F)$ and every Hecke character $\varphi$ of $(F_1)_A^\chi$. Here $\varphi^\sigma(x) = \varphi(x^\sigma)$, $x \in (F_1)_A^\chi$. Take $m \in \mathbb{Z}$ so that $(k_0 - k^0)/2 < m < (k_0 + k^0)/2$. By a theorem of Rohrlich [R], for every $\tilde{\epsilon} \in (\mathbb{Z}/2\mathbb{Z})^{J_{F_1}}$, we can find a Hecke character $\varphi$ of $(F_1)_A^\chi$ such that

\[L_f(m - \frac{k_0-1}{2}, \pi \otimes \varphi) \neq 0, \quad \varphi_\infty(x) = \prod_{\tau \in J_{F_1}} \text{sgn}(x_\tau)^{m+\tilde{\epsilon}(\tau)}, \quad x = (x_\tau) \in (F_1)_{\infty}^\chi.\]

Applying Theorem S, (I) to (5.2) taking $s = m - \frac{k_0-1}{2}$, we obtain

\[(5.3) \quad u(\tilde{\epsilon}^\sigma, \tilde{f}) \sim u(\tilde{\epsilon}, \tilde{f}) \quad \text{for every} \quad \sigma \in \text{Gal}(F_1/F),\]
where \( \tilde{\epsilon}(y) = \tilde{\epsilon}(\sigma y), \) \( y \in J_{F_1}. \) In a similar way, using Theorem 6.8 of [Y], we can derive the relation

\[
Q(\tilde{\chi}, \sigma \tilde{\delta}) \sim Q(\tilde{\chi}, \tilde{\delta}) \quad \text{for every } \emptyset \neq \tilde{\delta} \subseteq J_{F_1}.
\]

By (5.3) and (5.4), we get

\[
c_{\sigma \tau}^\pm(\tilde{\chi}) \sim c_{\tau}^\pm(\chi) \quad \text{for every } \sigma \in \text{Gal}(F_1/F), \quad \tau \in J_{F_1}
\]

in view of the uniqueness of the solution to (1) and (2) in the introduction. Taking \( \delta = \{\tau|F\}, \) \( \tau \in J_{F_1} \) in (1.7) and applying (5.5), we get

\[
c_{\tau}^\pm(\tilde{\chi})c_{\bar{\tau}}(\tilde{\chi}) \sim c_{\tau|F}^+(\chi)c_{\tau|F}^-(\chi), \quad \tau \in J_{F_1}.
\]

On the other hand, we have

\[
L_f(s, \tilde{\pi} \otimes (\varphi \circ N_{F_1/F})) = \prod_{\eta} L_f(s, \pi \otimes \varphi \eta)
\]

for every Hecke character \( \varphi \) of \( F_{A}^\times. \) Here \( \eta \) extends over \( l \) Hecke characters of \( F_{A}^\times \) which are trivial on \( F_{A}^\times N_{F_1/F}(F_{1})_{A}^\times, \) \( l \) being the degree of \( F_1 \) over \( F. \) Since \( k(\tau) \geq 3 \) for all \( \tau, \) we can apply Theorem S, (1) to this relation in a similar manner to the above and obtain

\[
u(\tilde{\epsilon}, \tilde{f}) \sim \nu(\epsilon, f)^{i} \quad \text{for every } \epsilon \in (\mathbb{Z}/2\mathbb{Z})^{J_F},
\]

where \( \tilde{\epsilon}(y) = \epsilon(y|F), \) \( y \in J_{F_1}. \) By (5.7) and (5.5), we get

\[
\prod_{\tau \in J_F} c_{\tilde{\tau}}^{\epsilon(\tau)}(\tilde{\chi}) \sim \prod_{\tau \in J_F} c_{\tilde{\tau}}^{\epsilon(\tau)}(\chi), \quad \text{for every } \epsilon \in (\mathbb{Z}/2\mathbb{Z})^{J_F},
\]

where \( \tilde{\tau} \) denotes an arbitrary extension of \( \tau \) to \( J_{F_1}. \)

Take any \( \tau_0 \in J_{F} \) and its extension \( \tilde{\tau}_0 \) to \( J_{F_1}. \) Take any \( \epsilon \in (\mathbb{Z}/2\mathbb{Z})^{J_F} \) and define \( \epsilon' \in (\mathbb{Z}/2\mathbb{Z})^{J_F} \) by

\[
\epsilon'(\tau) = -\epsilon(\tau) \quad \text{if } \tau \neq \tau_0, \quad \epsilon'(\tau_0) = \epsilon(\tau_0).
\]

We have

\[
\prod_{\tau \in J_F} c_{\tilde{\tau}}^{\epsilon(\tau)}(\tilde{\chi})c_{\tilde{\tau}}^{\epsilon'(\tau)}(\tilde{\chi}) \sim \left( \prod_{\tau \in J_F \setminus \{\tau_0\}} c_{\tilde{\tau}}^{\epsilon(\tau)}(\chi)c_{\tilde{\tau}}^{\epsilon'(\tau)}(\chi) \right) c_{\tau_0}^{\epsilon(\tau_0)}(\chi)^2
\]

by (5.6) and

\[
\prod_{\tau \in J_F} c_{\tilde{\tau}}^{\epsilon(\tau)}(\tilde{\chi})c_{\tilde{\tau}}^{\epsilon'(\tau)}(\tilde{\chi}) \sim \left( \prod_{\tau \in J_F \setminus \{\tau_0\}} c_{\tilde{\tau}}^{\epsilon(\tau)}(\chi)c_{\tilde{\tau}}^{\epsilon'(\tau)}(\chi) \right) c_{\tau_0}^{\epsilon(\tau_0)}(\chi)^2
\]

by (5.8). Hence we get

\[
c_{\tau_0}^{\epsilon(\tau_0)}(\chi)^2 \sim c_{\tau_0}^{\epsilon(\tau_0)}(\chi)^2.
\]

This completes the proof.
Remark. In this remark, we use left action of the automorphism group. For \( \sigma \in \text{Aut}(G) \), let \( \sigma(B) \) be the quaternion algebra over \( \sigma(F) \) obtained from \( B \) by transporting the algebra structure by the isomorphism \( \sigma : F \to \sigma(F) \). If \( B = \sum_{i=1}^{4} Fe_i \) with \( e_i e_j = \sum_{k=1}^{4} c_{ijk} e_k \), then \( \sigma(B) = \sum_{i=1}^{4} \sigma(F)e'_i \) with \( e'_i e'_j = \sum_{k=1}^{4} \sigma(c_{ijk})e'_k \). We have the isomorphism of \( Q \)-algebras \( \sigma : B \ni \sum a_i e_i \mapsto \sum \sigma(a_i)e'_i \in \sigma(B) \). If \( B \) is of signature \( (\delta, \delta') \), then \( \sigma(B) \) is of signature \( (\delta\sigma^{-1}, \delta'\sigma^{-1}) \). This isomorphism extends to the isomorphism (we use the same letter) \( G = \text{Res}_{F/Q}(B^X) \to \sigma(G) = \text{Res}_{\sigma(F)/Q}(\sigma(B)^X) \) and also from \( G_A \) to \( \sigma(G)_A \). For \( f \in S_{k,\kappa}(B) \), put \( \sigma(f)(x) = f(x), x \in G_A \). Then \( \sigma(f) \in S_{k',\kappa'}(\sigma(B)) \), where \( k'(\tau) = k(\tau\sigma), \kappa'(\tau) = \kappa(\tau\sigma), \tau \in J_{\sigma(F)} \).

If \( f \in W(\chi, B) \), then we see that \( \sigma(f) \in W(\sigma(\chi), \sigma(B)) \), where \( \sigma(\chi)(\sigma(m)) = \chi(m) \) for an integral ideal \( m \) of \( F \). We can check easily that \( (f, f) = (\sigma(f), \sigma(f)) \). We can verify that if \( f \) is \( \mathbb{Q} \)-rational, then \( \sigma(f) \) is \( \mathbb{Q} \)-rational. Therefore, both (5.3) and (5.4) hold under the condition \( k_0 \geq 2 \).

\( \text{§6. Comments on the case where } k(\tau) = 2 \text{ for some } \tau \)

We expect that our Main Theorem remains true under the weaker condition that \( k(\tau) \geq 2 \) for all \( \tau \in J_F \) and that \( k(\tau) \mod 2 \) is independent of \( \tau \). Let us first state necessary ingredients to prove Main Theorem in this generality by our method in this paper. Let \( \pi \) be the irreducible unitary cuspidal automorphic representation of \( GL(2, F_A) \) which corresponds to \( \chi \).

To prove Theorem 2 in this case by base change argument, it suffices to generalize (1.7) for any totally real quadratic extension \( F_1 \) of \( F \). For this purpose, the following Hypothesis is sufficient, as remarked in §6.4 of [Y].

**Hypothesis 1.** There exist a \( \text{CM-extension } K \) of \( F \) and a unitary Hecke character \( \psi \) of \( K_A^X \) which satisfy the following conditions.

1. \( \psi_v(x) = (x/|x|)^{l_v-1}, \quad x \in K_v^X \cong \mathbb{C}^X \) for \( v \in \mathfrak{a}^K \),

where \( l_v \) is a positive integer such that \( l_v < k_\tau \) if \( \tau \in \delta, l_\tau > k_\tau \) if \( \tau \in J_F \setminus \delta \) and that \( k_\tau - l_\tau \mod 2 \) is independent of \( \tau \). Here we put \( l_\tau = l_v \) taking \( v \in \mathfrak{a}^K \) such that \( |\tau|F = \tau \).

2. Let \( \pi' \) be the irreducible unitary automorphic representation of \( GL(2, F_A) \) which corresponds to \( \psi \). Then \( L(\frac{1}{2}, \pi \times \pi') L(\frac{1}{2}, \pi \times \pi' \otimes \eta_{F_1}) \neq 0 \).

Here \( L(s, \pi \times \pi') \) denotes the L-function obtained by the convolution of \( \pi \) and \( \pi' \); \( \eta_{F_1} \) is the Hecke character of \( F_A^X \) which corresponds to the extension \( F_1/F \).

Similarly Theorem 3 can be proved in this generality if the following Hypothesis is valid. Assume \( k(\tau) = 2 \) for some \( \tau \in J_F \).

**Hypothesis 2.** We use the same notation as in the proof of Theorem 3. There exist a quadratic extension \( K \) of \( F \) and a Hecke characters \( \varphi_1, \psi_1 \) of \( F_A^X \) which satisfy the following conditions.

1. \( (\varphi_1)_\infty \) and \( (\psi_1)_\infty \) are given by (4.5) with \( m_0 = k_0/2 \).
(2) $K$ is ramified at $\tau \in J_F$ if and only if $\{\epsilon_1(\tau), \epsilon_2(\tau)\} = \{0,1\}$.

(3) $L(\frac{1}{2}, \pi \otimes \varphi_1) L(\frac{1}{2}, \pi \otimes \varphi_1 \eta_K) \neq 0$, $L(\frac{1}{2}, \pi \otimes \psi_1) L(\frac{1}{2}, \pi \otimes \psi_1 \eta_K) \neq 0$,

where $\eta_K$ is the Hecke character of $F_A^\chi$ which corresponds to the extension $K/F$.

If these two Hypotheses are valid, Main Theorem holds under the weaker condition stated above. These hypotheses, in which we require simultaneous non-vanishing, are somewhat beyond our present knowledge. We only mention Harris [Ha4], Rohrlich [R] and Waldspurger [W] as papers treating related subjects.

When $k(\tau) = 2$ for all $\tau$, Shimura proposed a construction of an abelian variety from critical values of $D(s, \chi, \varphi)$ in [S5], §11. If it were shown that that these abelian varieties have models over $\overline{Q}$, as is well known when $F = Q$, this construction would imply a still deeper assertion on the nature of critical values. If we could prove Main Theorem also in this case, Shimura’s periods in [S5], §11 essentially coincide with $c^\pm_\tau(\chi)$, since $P(\chi, \{\tau\}, \epsilon) \sim \pi^{-1}c^\epsilon_\tau(\chi)$.

References


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