

GAUSS SUMS AND KLOOSTERMAN SUMS OVER RESIDUE RINGS OF ALGEBRAIC INTEGERS

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ABSTRACT. Let \mathcal{O} denote the ring of integers of an algebraic number field of degree m which is totally and tamely ramified at the prime p . Write $\zeta_q = \exp(2\pi i/q)$, where $q = p^r$. We evaluate the twisted Kloosterman sum

$$\sum_{\alpha \in (\mathcal{O}/q\mathcal{O})^*} \chi(N(\alpha)) \zeta_q^{T(\alpha)+z/N(\alpha)},$$

where T and N denote trace and norm, and where χ is a Dirichlet character (mod q). This extends results of Salié for $m = 1$ and of Yangbo Ye for prime m dividing $p - 1$. Our method is based upon our evaluation of the Gauss sum

$$\sum_{\alpha \in (\mathcal{O}/q\mathcal{O})^*} \chi(N(\alpha)) \zeta_q^{T(\alpha)},$$

which extends results of Mauclairé for $m = 1$.

1. INTRODUCTION

Let E be a field of degree m over \mathbb{Q} , and let \mathcal{O}_E denote the ring of integers in E . Suppose that p is a prime and $\mathfrak{P} \subset \mathcal{O}_E$ is a prime ideal such that

$$(1.1) \quad p\mathcal{O}_E = \mathfrak{P}^m, \quad p \nmid m,$$

that is, p is totally and tamely ramified in E . For

$$(1.2) \quad q = p^r, \quad r \geq 1,$$

consider the finite quotient rings

$$(1.3) \quad R_q = \mathbb{Z}/q\mathbb{Z}, \quad \mathcal{O}_q = \mathcal{O}_E/q\mathcal{O}_E,$$

which have cardinalities q and q^m , respectively. For $\alpha \in \mathcal{O}_E$ viewed as an element of \mathcal{O}_q , write $N(\alpha)$ and $T(\alpha)$ to denote the norm and trace of α from \mathcal{O}_q to R_q . For any positive integer n , set

$$(1.4) \quad \zeta_n = \exp(2\pi i/n).$$

For Dirichlet characters χ, η (mod q) and $z \in R_q^*$, define the Gauss sum

$$(1.5) \quad G(\chi) = G_m(\chi) = \sum_{\alpha \in \mathcal{O}_q^*} \chi(N(\alpha)) \zeta_q^{T(\alpha)}$$

and the (twisted) Kloosterman sum

$$(1.6) \quad K(\eta, z) = K_m(\eta, z) = \sum_{\alpha \in \mathcal{O}_q^*} \eta(N(\alpha)) \zeta_q^{T(\alpha)+z/N(\alpha)}.$$

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In the case that η is the trivial character, write $\eta = 1$ and set

$$K(z) = K(1, z).$$

The sums in (1.5) - (1.6) are well-defined, since the summands would be unchanged if a multiple of q were added to α .

Mauclaire [9], [10], [2, Theorem 1.6.4, p. 40], Odoni [12], [2, Theorem 1.6.2, p. 33], and Funakura [6], [2, Theorem 1.6.3, p. 37] explicitly evaluated the Gauss sums $G_1(\chi)$ for all $r \geq 2$. In §2 (Theorem 2.2), we extend Mauclaire's results by evaluating the Gauss sums $G_m(\chi)$ for all m .

Salié [13] evaluated the Kloosterman sums $K_1(1, z)$ for all $r \geq 2$. Ye [16] evaluated the Kloosterman sums $K_m(1, z)$ in terms of a twisted hyper-Kloosterman sum over R_q^* , in the case that m is prime, $m|(p-1)$, and E/\mathbb{Q} is cyclic; see (3.1). In §3 (Theorem 3.2), we apply Theorem 2.2 to extend Ye's result in the case $r \geq 2$ by evaluating $K_m(\eta, z)$ for all m (where m need not be a prime nor a divisor of $p-1$). Our evaluations are in terms of twisted hyper-Kloosterman sums over R_q^* which in turn have been explicitly evaluated in [5]. In Theorem 3.3, we extend Ye's result in the case $r = 1$ by evaluating $K_m(1, z)$ for all (not necessarily prime) m dividing $p-1$.

In contrast with Ye's determination, we do not require results from local class field theory. Our proof requires only relatively basic results from local and global algebraic number theory.

Ye [18] has pointed out that the results of [16] can be generalized to cyclic extensions E of composite degree m over \mathbb{Q} , by applying repeated liftings of prime degree as in Arthur and Clozel [1, Eq. (6.7), p. 60]. For work related to [16] where the prime p is unramified in E , see Ye [17]. We note that in both [16] and [17], E is assumed to be cyclic over \mathbb{Q} , whereas in this paper, there is no such restriction.

In §4 (Theorem 4.1), we give a general product formula for the Gauss sums $G_m(\chi)$, which reduces in the case $m = r = 1$ to the famous Davenport-Hasse product formula [3], [2, Theorem 11.3.5, p. 355] for Gauss sums (mod p) given in (3.16).

2. EVALUATION OF GAUSS SUMS $G_m(\chi)$

In the case $m = 1$, the Gauss sum $G_m(\chi)$ over \mathcal{O}_q^* reduces to the familiar Gauss sum $G_1(\chi)$ over R_q^* defined by

$$(2.1) \quad G_1(\chi) = \sum_{a \in R_q^*} \chi(a) \zeta_q^a.$$

No explicit evaluation of $G_1(\chi)$ is known for general χ in the case $r = 1$ (i.e., $q = p$), but for $r \geq 2$, $G_1(\chi)$ can be evaluated as follows. We have

$$(2.2) \quad G_1(\chi) = 0 \text{ if } \chi \text{ is nonprimitive, } r \geq 2$$

(see [2, Eqs. (1.6.4)–(1.6.5)]). If $r \geq 2$ and χ is primitive, then

$$(2.3) \quad G_1(\chi) = \begin{cases} \sqrt{q} \zeta_q, & \text{if } r \text{ is even,} \\ \sqrt{q} \zeta_q \zeta_8^{1-p}, & \text{if } p > 2 \text{ and } r \geq 3 \text{ is odd,} \\ \sqrt{q} \zeta_q \zeta_8, & \text{if } p = 2 \text{ and } r \geq 5 \text{ is odd,} \\ \sqrt{q} \zeta_q \zeta_8^{-\chi(-1)}, & \text{if } p = 2 \text{ and } r = 3, \end{cases}$$

provided that $\nu(\chi) = 1$, where $\nu = \nu(\chi)$ is defined for $r \geq 2$ by

$$(2.4) \quad \chi(1 + p^s) = \zeta_{p^s}^{-\nu}, \quad \text{for even } r = 2s \geq 2,$$

$$(2.5) \quad \chi(5) = (-1)^\nu, \quad \text{for } q = 8 \text{ (i.e., } p = 2, r = 3),$$

and

$$(2.6) \quad \chi(1 + p^s + \frac{1}{2}p^{2s}) = \zeta_{p^{s+1}}^{-\nu}, \quad \text{for odd } r = 2s + 1 \geq 3, \quad q \neq 8.$$

(In (2.6) and in the sequel, $\frac{1}{2}(\bmod p)$ is interpreted as $(p + 1)/2 \pmod{p}$ when $p > 2$.)

The evaluation of $G_1(\chi)$ in (2.3) was proved by Mauclaire [9], [10]. For a shortened proof, see [2, Theorem 1.6.4, p. 40] (where “inner sum on y ” should be corrected to read “inner sum on x ” in [2, p. 41]).

For $r \geq 2$, the assertion that χ is primitive is equivalent to the assertion that p does not divide $\nu(\chi)$. When $r \geq 2$ and $\nu(\chi) = 1$, the (primitive) character χ is said to be *normalized*. When $r \geq 2$ and χ is primitive but not necessarily normalized, we can evaluate $G_1(\chi)$ in terms of a normalized Gauss sum in (2.3), as follows. First write

$$(2.7) \quad \chi = \xi^\nu,$$

where ξ is a normalized character $(\bmod q)$, and $\nu = \nu(\chi)$ is chosen relatively prime to $q(p - 1)$. Then

$$(2.8) \quad G_1(\chi) = G_1(\xi^\nu) = \chi(\nu)\sigma_\nu(G_1(\xi)),$$

where $\sigma_\nu \in \text{Gal}(\mathbb{Q}(\zeta_{q(p-1)})/\mathbb{Q})$ is defined by $\sigma_\nu(\zeta_{q(p-1)}) = \zeta_{q(p-1)}^\nu$. Since $G_1(\xi)$ is evaluated in (2.3), we see that (2.8) yields an evaluation of $G_1(\chi)$ for any primitive character χ , when $r \geq 2$.

In Theorem 2.2 below, we extend the evaluations of $G_1(\chi)$ given above by evaluating the Gauss sums $G_m(\chi)$ for *all* m . We begin with a lemma which gives a useful representation of the elements of \mathcal{O}_q . While its proof is p -adic, the lemma allows us to prove our main results in the language of global rather than local rings.

Lemma 2.1. *There exists $\tau \in \mathcal{O}_E$ of degree m over \mathbb{Q} such that*

$$(2.9) \quad \tau^m \equiv pu \pmod{q\mathcal{O}_E} \text{ for some integer } u \not\equiv 0 \pmod{p},$$

$$(2.10) \quad \text{Tr}_{E/\mathbb{Q}}(\tau^i) \equiv 0 \pmod{q} \quad (1 \leq i \leq m - 1),$$

and

$$(2.11) \quad \mathcal{O}_q = \left\{ \sum_{i=0}^{m-1} \alpha_i \tau^i : \alpha_i \in R_q \right\}.$$

Moreover, the m conjugates of τ over \mathbb{Q} have the form $\tau \zeta_m^i + q\beta_i$, $1 \leq i \leq m$, where the β_i are algebraic integers.

Proof. Choose any $\omega \in \mathcal{O}_E$ with $\mathfrak{P} \parallel \omega$, i.e., $\omega \in \mathfrak{P} - \mathfrak{P}^2$. Then the irreducible polynomial of ω over \mathbb{Q} is p -Eisensteinian of degree m , and $E = \mathbb{Q}(\omega)$. We also have [11, Theorem 5.5, p. 217] $E_{\mathfrak{P}} = \mathbb{Q}_p(\omega)$ and $[E_{\mathfrak{P}} : \mathbb{Q}_p] = m$, where $E_{\mathfrak{P}}$ is the \mathfrak{P} -adic completion of E , and \mathbb{Q}_p denotes the p -adic rationals. Let \mathbb{Z}_p denote the p -adic integers. By [8, Ex. 13-14, pp. 74, 140] (cf. [15, pp. 324–325]), there exists an element $\pi \in E_{\mathfrak{P}}$ such that

$$(2.12) \quad E_{\mathfrak{P}} = \mathbb{Q}_p(\pi), \quad \mathcal{O}_{E_{\mathfrak{P}}} = \mathbb{Z}_p(\pi),$$

$$(2.13) \quad \pi^m = p\mu, \quad \text{for some } \mu \in \mathbb{Z}_p^*,$$

$$(2.14) \quad \pi \mathcal{O}_{E_{\mathfrak{P}}} = \mathfrak{P} \mathcal{O}_{E_{\mathfrak{P}}},$$

and

$$(2.15) \quad \pi - \omega \in \mathfrak{P}^2 \mathcal{O}_{E_{\mathfrak{P}}}.$$

Since $X^m - p\mu$ is the irreducible polynomial of π over \mathbb{Q}_p , the m conjugates of π over \mathbb{Q}_p are $\pi \delta^j$ ($0 \leq j \leq m - 1$), where δ is a primitive m -th root of unity in a field extension of \mathbb{Q}_p . Thus

$$(2.16) \quad \text{Tr}_{E_{\mathfrak{P}}/\mathbb{Q}_p}(\pi^i) = 0, \quad 1 \leq i \leq m - 1,$$

where Tr denotes the trace. By (2.12)–(2.13), every $\alpha \in \mathcal{O}_E$ can be π -adically represented in the form

$$(2.17) \quad \alpha = \sum_{i=0}^{m-1} a_i \pi^i, \quad a_i \in \mathbb{Z}_p.$$

We can find $\tau \in \mathcal{O}_E$ such that

$$(2.18) \quad \tau \equiv \pi \pmod{q \mathcal{O}_{E_{\mathfrak{P}}}},$$

by reducing (mod q) an appropriate linear combination of $\omega, \omega^2, \dots, \omega^{m-1}$ over \mathbb{Z}_p . Then τ has degree m over \mathbb{Q} , by the same argument we used to show that ω has degree m over \mathbb{Q} . By (2.13) and (2.18), we see that (2.9) holds for some integer u with $u \equiv \mu \pmod{q \mathbb{Z}_p}$. By (2.16), (2.18) and the fact that

$$\text{Tr}_{E_{\mathfrak{P}}/\mathbb{Q}_p}(\tau^i) = \text{Tr}_{E/\mathbb{Q}}(\tau^i)$$

[11, Corollary, p. 266], we see that (2.10) holds. Equality (2.11) follows easily from (2.17) - (2.18). The last assertion of the lemma results from applying the m different \mathbb{Q}_p -embeddings of $E_{\mathfrak{P}}$ to both sides of (2.18). \square

We now evaluate the Gauss sums $G(\chi) = G_m(\chi)$ over \mathcal{O}_q^* in terms of the Gauss sums $G_1(\chi)$ over R_q^* discussed at the beginning of this section.

Theorem 2.2. *If $r = 1$, then*

$$(2.19) \quad G(\chi) = p^{m-1} \overline{\chi}^m(m) G_1(\chi^m).$$

If $r \geq 2$ and χ is nonprimitive, then $G(\chi) = 0$. If $r \geq 2$ and χ is primitive, then, with $\nu(\chi)$ defined by (2.4) – (2.6),

$$(2.20) \quad G(\chi) = \begin{cases} G_1(\chi)^m p^{(m-1)/2} \left(\frac{p}{m}\right)^r, & \text{if } 2 \nmid m, \\ G_1(\chi)^m p^{(m-1)/2} \zeta_8^{(1-p)(1-m)} \left(\frac{-Dp^{1-m}}{p}\right)^{r+1} \left(\frac{m\nu(\chi)}{p}\right), & \text{if } 2|m, \end{cases}$$

where D is the discriminant of the number field E , and where $G_1(\chi)$ is explicitly given by (2.8).

Remark. If $2|m$, then $p > 2$ by (1.1). Moreover, $p^{m-1} \parallel D$ by [11, Theorem 4.8, p. 166]. Hence the Legendre symbols in (2.20) make sense. For a formulation of (2.20) in the case $2|m$ in which $\nu(\chi)$ does not appear, see (2.45).

Proof. For $\alpha \in \mathcal{O}_q$, write

$$(2.21) \quad \alpha = \sum_{i=0}^{m-1} \alpha_i \tau^i, \quad \alpha_i \in R_q,$$

as in (2.11). First suppose that $r = 1$, so that $q = p$. Recall the definitions of T and N below (1.3). By Lemma 2.1, $T(\alpha) = m\alpha_0$ and $N(\alpha) = \alpha_0^m$, since $q = p$. Thus

$$G(\chi) = \sum_{\alpha_0, \dots, \alpha_{m-1} \in R_p} \chi(\alpha_0^m) \zeta_p^{m\alpha_0} = p^{m-1} \sum_{a \in R_p} \chi^m(a) \zeta_p^{ma} = p^{m-1} \overline{\chi}^m(m) G_1(\chi^m),$$

which proves (2.19).

Suppose now that $r \geq 2$. If χ is nonprimitive, then $G(\chi) = 0$ by an argument analogous to that proving (2.2). Next assume that χ is primitive. If $m = 1$, then (2.20) follows from the definition (2.1) of $G_1(\chi)$. Hence assume that $m > 1$.

We first prove (2.20) when χ is normalized. There are three cases.

Case 1: $\nu(\chi) = 1$, $r = 2s$, $s \geq 1$.

The elements $\alpha \in \mathcal{O}_q^*$ may be written

$$\alpha = z + zw p^s \quad (z \in \mathcal{O}_{p^s}^*, w \in \mathcal{O}_{p^s}),$$

so

$$G(\chi) = \sum_{z \in \mathcal{O}_{p^s}^*} \chi(N(z)) \zeta_q^{T(z)} \sum_{w \in \mathcal{O}_{p^s}} \chi(N(1 + wp^s)) \zeta_{p^s}^{T(zw)}.$$

Since

$$N(1 + wp^s) = 1 + T(w)p^s \equiv (1 + p^s)^{T(w)} \pmod{q},$$

it follows from the normalization (2.4) that

$$G(\chi) = \sum_z \chi(N(z)) \zeta_q^{T(z)} \sum_w \zeta_{p^s}^{T(w(z-1))}.$$

Using Lemma 2.1, one sees that the inner sum \sum_w vanishes unless $z \equiv 1 \pmod{\tau p^{s-1}}$,

in which case

$$\sum_w = \text{Card}(\mathcal{O}_{p^s}) = p^{sm} = (\sqrt{q})^m.$$

Thus, writing $z = 1 + xp^{s-1}$ with

$$x := \sum_{i=1}^{m-1} x_i \tau^i \in \mathcal{O}_p \quad (x_1, \dots, x_{m-1} \in R_p),$$

we have

$$(2.22) \quad G(\chi) = (\sqrt{q}\zeta_q)^m \sum_{x_1, \dots, x_{m-1} \in R_p} \chi(N(1 + xp^{s-1})).$$

Write $N(1 + xp^{s-1})$ as a product of m conjugates and expand. One sees, using Lemma 2.1, that

$$(2.23) \quad N(1 + xp^{s-1}) = 1 - p^{2s-1} \left\{ \frac{mu}{2} \sum_{i=1}^{m-1} x_i x_{m-i} + f(x_1, \dots, x_{m-1}) \right\},$$

where $f(x_1, \dots, x_{m-1})$ is a \mathbb{Z} -linear combination of monomials $x_{i_1} \dots x_{i_n}$ with $3 \leq n \leq m$, $i_1 + \dots + i_n = m$. If $m = 2$, f is interpreted as 0. (Note that each coefficient in f is divisible by p^{s-1} , so the term f could have been omitted from (2.23) were it not for the pesky case $s = 1$.) Since

$$N(1 + xp^{s-1}) = (1 + p^s)^{-p^{s-1}} \left\{ \frac{mu}{2} \sum_{i=1}^{m-1} x_i x_{m-i} + f(x_1, \dots, x_{m-1}) \right\},$$

the normalization (2.4) gives

$$\chi(N(1 + xp^{s-1})) = \zeta_p^{\frac{mu}{2} \sum_{i=1}^{m-1} x_i x_{m-i} + f(x_1, \dots, x_{m-1})}.$$

Therefore, by (2.22) and (2.3),

$$(2.24) \quad G_1(\chi)^{-m} G(\chi) = \sum_{x_1, \dots, x_{m-1} \in R_p} \zeta_p^{\frac{mu}{2} \sum_{i=1}^{m-1} x_i x_{m-i} + f(x_1, \dots, x_{m-1})}.$$

Now, x_{m-1} does not actually appear in the polynomial $f(x_1, \dots, x_{m-1})$ and so unless $x_1 = 0$, the sum on x_{m-1} in (2.24) vanishes when $m > 2$. Therefore we may set $x_1 = 0$ in the summands of (2.24) when $m > 2$. Further, x_{m-2} does not appear in the polynomial $f(0, x_2, \dots, x_{m-1})$, and so unless $x_2 = 0$, the sum on x_{m-2} vanishes when $m > 4$. Continuing in this way, we see that one may set

$$x_1 = x_2 = \dots = x_{\lfloor (m-1)/2 \rfloor} = 0$$

in the summands of (2.24). With this substitution, all terms of the polynomial f vanish, and so (2.24) becomes

$$(2.25) \quad G_1(\chi)^{-m} G(\chi) = \begin{cases} p^{(m-1)/2}, & \text{if } 2 \nmid m, \\ p^{(m-2)/2} \sum_{y=0}^{p-1} \zeta_p^{muy^2/2}, & \text{if } 2 \mid m, \end{cases}$$

where we've written y for the variable $x_{m/2}$. This proves (2.20) for odd m . Assume now that $2 \mid m$. Then

$$(2.26) \quad \sum_{y=0}^{p-1} \zeta_p^{muy^2/2} = \sqrt{p} \left(\frac{mu}{p} \right) \zeta_8^{(1-p)(1-m)} \left(\frac{-1}{p} \right)^{m/2}$$

(see [2, Theorem 1.5.2, p. 26]). In view of (2.25) - (2.26), it remains to prove that

$$(2.27) \quad \left(\frac{u}{p}\right) = \left(\frac{-1}{p}\right)^{m/2} \left(\frac{-Dp^{1-m}}{p}\right).$$

By Lemma 2.1,

$$N_{E/\mathbb{Q}}(\tau) \equiv -pu \pmod{q},$$

so by (2.18), $N := N_{E_{\mathbb{F}}/\mathbb{Q}_p}(\pi)$ satisfies

$$\left(\frac{u}{p}\right) = \left(\frac{-N/p}{p}\right).$$

By (2.15),

$$N_{E/\mathbb{Q}}(\omega)/p \equiv N/p \pmod{p\mathbb{Z}_p},$$

and so

$$(2.28) \quad \left(\frac{u}{p}\right) = \left(\frac{-N/p}{p}\right) = \left(\frac{-(N_{E/\mathbb{Q}}(\omega)/p)^{m-1}}{p}\right),$$

where the last equality uses the fact that m is even. Let $g(x) \in \mathbb{Z}[x]$ denote the (p -Eisensteinian) irreducible polynomial of ω over \mathbb{Q} , discussed near the beginning of the proof of Lemma 2.1. Since

$$g'(\omega) \equiv m\omega^{m-1} \pmod{p\mathcal{O}_E}$$

and m is even, (2.28) yields

$$(2.29) \quad \left(\frac{u}{p}\right) = \left(\frac{-N_{E/\mathbb{Q}}(g'(\omega))p^{1-m}}{p}\right).$$

By a well-known formula for the discriminant of the basis $1, \omega, \dots, \omega^{m-1}$ for E [11, Prop. 2.4, p. 53], the “numerator” on the right side of (2.29) may be replaced by $(-1)^{(m+2)/2} Dp^{1-m}$. This proves (2.27) and completes the proof of (2.20) in Case 1.

Case 2: $\nu(\chi) = 1, r = 2s + 1, s \geq 1, q \neq 8$.

In this case, $s > 1$ when $p = 2$. The elements $\alpha \in \mathcal{O}_q^*$ may be written

$$\alpha = z + zwp^s \quad (z \in \mathcal{O}_{p^s}^*, w \in \mathcal{O}_{p^{s+1}}),$$

so

$$G(\chi) = \sum_{z \in \mathcal{O}_{p^s}^*} \chi(N(z))\zeta_q^{T(z)} \sum_{w \in \mathcal{O}_{p^{s+1}}} \chi(N(1 + wp^s))\zeta_{p^{s+1}}^{T(zw)}.$$

Observe that

$$N(1 + wp^s) = 1 + p^s T(w) + \frac{1}{2} p^{2s} (T(w)^2 - T(w^2)),$$

so since $s > 1$ when $p = 2$,

$$N(1 + wp^s) = (1 + p^s + \frac{1}{2} p^{2s})^{T(w - p^s w^2/2)}.$$

It thus follows from the normalization (2.6) that

$$(2.30) \quad G(\chi) = \sum_{z \in \mathcal{O}_{p^s}^*} \chi(N(z))\zeta_q^{T(z)} S(z),$$

where

$$S(z) = \sum_{w \in \mathcal{O}_{p^{s+1}}} \zeta_{p^{s+1}}^{T(zw+p^s w^2/2-w)}.$$

Writing

$$w = x + yp^s \quad (x \in \mathcal{O}_{p^s}, y \in \mathcal{O}_p),$$

we have

$$S(z) = \sum_x \zeta_{p^{s+1}}^{T(x(z-1)+x^2 p^s/2)} \sum_y \zeta_p^{T(y(z-1))}.$$

The inner sum \sum_y vanishes unless $z \equiv 1 \pmod{\tau}$, in which case $\sum_y = p^m$. Thus set

$$(2.31) \quad z = 1 + \sum_{i=1}^{m-1} z_i \tau^i, \quad z_i \in R_{p^s}.$$

Writing

$$x = a + bp \quad (a \in \mathcal{O}_p, b \in \mathcal{O}_{p^{s-1}}),$$

we have

$$(2.32) \quad S(z) = p^m \sum_a \zeta_p^{T(a^2/2)} \zeta_{p^{s+1}}^{T(a(z-1))} U(z),$$

where

$$U(z) = \sum_{b \in \mathcal{O}_{p^{s-1}}} \zeta_{p^s}^{T(b(z-1))}.$$

Writing

$$b = \sum_{i=0}^{m-1} b_i \tau^i, \quad b_i \in R_{p^{s-1}},$$

we have, by (2.31) and Lemma 2.1,

$$U(z) = \sum_{b_0, \dots, b_{m-1}} \zeta_{p^s}^{mpu \sum_{i=1}^{m-1} z_i b_{m-i}} = \sum_{b_0, \dots, b_{m-1}} \zeta_{p^{s-1}}^{mu \sum_{i=1}^{m-1} z_i b_{m-i}}.$$

Therefore $U(z)$ vanishes unless p^{s-1} divides each of z_1, z_2, \dots, z_{m-1} , in which case $U(z) = p^{m(s-1)}$. Thus, with

$$z = 1 + p^{s-1} \sum_{i=1}^{m-1} q_i \tau^i, \quad q_i \in R_p,$$

(2.32) becomes

$$S(z) = p^{sm} \sum_{a \in \mathcal{O}_p} \zeta_p^{T(a^2/2)} \zeta_{p^2}^{T(a \sum_{i=1}^{m-1} q_i \tau^i)}.$$

Writing

$$a = \sum_{i=0}^{m-1} a_i \tau^i, \quad a_i \in R_p,$$

we obtain

$$S(z) = p^{sm} \sum_{a_0, \dots, a_{m-1}} \zeta_p^{ma_0^2/2 + mu \sum_{i=1}^{m-1} a_{m-i} q_i}.$$

Thus $S(z)$ vanishes unless $q_1 = \dots = q_{m-1} = 0$, i.e., $S(z)$ vanishes unless $z = 1$. Since

$$S(1) = p^{sm+(m-1)} \sum_{d \in R_p} \zeta_p^{md^2/2},$$

(2.30) yields

$$\begin{aligned} G(\chi) &= \zeta_q^m p^{m(s+1/2)} p^{m/2-1} \sum_{d \in R_p} \zeta_p^{md^2/2} \\ (2.33) \quad &= (\zeta_q \sqrt{q})^m p^{m/2-1} \sum_{d \in R_p} \zeta_p^{md^2/2}. \end{aligned}$$

By (2.3),

$$(2.34) \quad (\sqrt{q} \zeta_q)^m = \begin{cases} G_1(\chi)^m \zeta_8^{-m(1-p)}, & \text{if } p > 2, \\ G_1(\chi)^m \zeta_8^{-m}, & \text{if } p = 2. \end{cases}$$

By [2, Theorem 1.5.2, p. 26],

$$(2.35) \quad \sum_{d \in R_p} \zeta_p^{md^2/2} = \begin{cases} \sqrt{p} \left(\frac{m}{p}\right) \zeta_8^{1-p}, & \text{if } p > 2, \\ 1 + i^m = \sqrt{p} \left(\frac{p}{m}\right) \zeta_8^m, & \text{if } p = 2. \end{cases}$$

When p and m are odd, the law of quadratic reciprocity gives

$$(2.36) \quad \left(\frac{p}{m}\right) = \left(\frac{m}{p}\right) \zeta_8^{(1-p)(1-m)}.$$

Combining (2.33) - (2.36), we complete the proof of (2.20) in Case 2.

Case 3: $\nu(\chi) = 1$, $q = 8$.

The elements $\alpha \in \mathcal{O}_8^*$ can be written

$$\alpha = a + 2ab \quad (a \in \mathcal{O}_2^*, b \in \mathcal{O}_4),$$

so

$$(2.37) \quad G(\chi) = \sum_{a \in \mathcal{O}_2^*} \chi(N(a)) \zeta_8^{T(a)} \sum_{b \in \mathcal{O}_4} \chi(N(1+2b)) \zeta_4^{T(ab)}.$$

Observe that

$$(2.38) \quad N(1+2b) = 1 + 2T(b) + 2(T(b)^2 - T(b^2)).$$

Write

$$a = 1 + \sum_{i=1}^{m-1} a_i \tau^i, \quad a_i \in R_2,$$

and

$$b = \sum_{i=0}^{m-1} b_i \tau^i, \quad b_i \in R_4.$$

We have $T(b) = mb_0$, and, since m is odd, $T(b)^2 = m^2b_0^2 = b_0^2$. Also,

$$T(b^2) = T(b_0^2) + T(2u \sum_{i=1}^{m-1} b_i b_{m-i}).$$

Since m is odd, $\sum b_i b_{m-i}$ is even, so

$$2T(b^2) = 2T(b_0^2) = 2mb_0^2.$$

Thus (2.38) becomes

$$(2.39) \quad N(1 + 2b) = 1 + 2mb_0 + 2b_0^2 - 2mb_0^2.$$

Now,

$$(2.40) \quad T(ab) = mb_0 + 2mu \sum_{i=1}^{m-1} a_i b_{m-i}.$$

By (2.39) - (2.40), we see that (2.37) becomes

$$(2.41) \quad G(\chi) = \sum_{a \in \mathcal{O}_2^*} \chi(N(a)) \zeta_8^{T(a)} \sum_{b_0 \in R_4} \chi(1 + 2mb_0 + 2b_0^2(1 - m)) \zeta_4^{mb_0} \\ \times \sum_{b_1, \dots, b_{m-1} \in R_4} (-1)^{\sum_{i=1}^{m-1} a_i b_{m-i}}.$$

The inner sum on b_1, \dots, b_{m-1} vanishes unless a_1, \dots, a_{m-1} are all even, in which case $a = 1$ and this inner sum equals 4^{m-1} . Thus (2.41) becomes

$$G(\chi) = \zeta_8^m 4^{m-1} \sum_{b_0 \in R_4} \chi(1 + 2mb_0 + 2b_0^2(1 - m)) \zeta_4^{mb_0} \\ = \zeta_8^m 4^{m-1} \{1 + \chi(3)\zeta_4^m + \chi(5)\zeta_4^{2m} + \chi(7)\zeta_4^{3m}\}.$$

Since $\chi(5) = -1$ by (2.5),

$$G(\chi) = \zeta_8^m 4^{m-1} \{1 - \chi(-1)\zeta_4^m + 1 - \chi(-1)\zeta_4^m\} \\ = \zeta_8^m 2^{2m-1} \{1 - \chi(-1)\zeta_4^m\} \\ = \left(\sqrt{8}\zeta_8^{1-\chi(-1)}\right)^m 2^{(m-1)/2} \left(\frac{2}{m}\right) \\ = G_1(\chi)^m 2^{(m-1)/2} \left(\frac{2}{m}\right),$$

where the last equality follows from (2.3). This proves (2.20) in Case 3, which completes the proof of (2.20) for normalized χ .

We now drop the assumption that χ is normalized, and consider the general situation where χ is given by (2.7). For brevity, we rewrite (2.20) in the normalized case as

$$(2.42) \quad G(\xi) = G_1(\xi)^m A(m),$$

where

$$(2.43) \quad A(m) = \begin{cases} \left(\frac{p}{m}\right)^r p^{(m-1)/2}, & \text{if } 2 \nmid m, \\ \zeta_8^{(1-p)(1-m)} \left(\frac{m}{p}\right) \left(\frac{-Dp^{1-m}}{p}\right)^{r+1} p^{(m-1)/2}, & \text{if } 2 \mid m. \end{cases}$$

Applying the automorphism σ_ν to both sides of (2.42), we have, by (2.7) and (2.8),

$$G(\chi) = G_1(\chi)^m \sigma_\nu(A(m)).$$

To prove (2.20), it remains to show that

$$(2.44) \quad \sigma_\nu(A(m)) = \begin{cases} A(m), & \text{if } 2 \nmid m, \\ \left(\frac{\nu}{p}\right) A(m), & \text{if } 2|m. \end{cases}$$

If $2 \nmid m$, (2.44) follows because $A(m) \in \mathbb{Z}$. Now suppose that $2|m$ (so that $p > 2$). Then $A(m) = n\sqrt{pi}^{(p-1)^2/4}$ for some $n \in \mathbb{Z}$. Now (2.44) follows since

$$\sqrt{pi}^{(p-1)^2/4} = \sum_{x=0}^{p-1} \zeta_p^{x^2}$$

(see [2, Theorem 1.2.4, p. 15]) and

$$\sigma_\nu \left(\sum_{x=0}^{p-1} \zeta_p^{x^2} \right) = \left(\frac{\nu}{p} \right) \sum_{x=0}^{p-1} \zeta_p^{x^2}.$$

□

We remark that in the case $2|m$, (2.20) can also be written

$$(2.45) \quad G(\chi) = G_1(\chi)^{m-1} G_1(\chi\phi) p^{(m-1)/2} \zeta_8^{(1-p)(1-m)} \left(\frac{-Dp^{1-m}}{p} \right)^{r+1} \left(\frac{m}{p} \right), \text{ if } r \geq 2,$$

where ϕ is the Legendre symbol, viz., $\phi(x) = \left(\frac{x}{p}\right)$. To see this, write $\chi = \xi^\nu$ as in (2.7). In view of (2.4) - (2.6), $\nu(\xi\phi) = 1$, so $G_1(\xi\phi) = G_1(\xi)$ by (2.3); then, applying σ_ν to both sides of this equality, we obtain, by (2.8),

$$(2.46) \quad G_1(\chi\phi) = \left(\frac{\nu(\chi)}{p} \right) G_1(\chi), \text{ if } r \geq 2.$$

3. EVALUATION OF KLOOSTERMAN SUMS $K(\eta, z)$

In the case that E/\mathbb{Q} is cyclic, p is an odd prime, and m is a prime dividing $(p - 1)$, Ye [16, Theorem 1] gave essentially the following evaluation of the Kloosterman sum $K(z)$ (defined below (1.6)):

$$(3.1) \quad K(z) = p^{(m-1)/2} \left(\frac{m}{p} \right) \left(\frac{-Dp^{1-m}}{p} \right)^{(m+1)(r+1)} \zeta_8^{(1-p)(1-m)} H(z), \quad z \in R_q^*,$$

where $H(z)$ is the twisted hyper-Kloosterman sum defined by

$$(3.2) \quad H(z) = \sum_{x_1, \dots, x_m \in R_q^*} \psi(x_2 x_3^2 \cdots x_m^{m-1}) \zeta_q^{x_1 + \cdots + x_m + z/(x_1 \cdots x_m)}$$

for any character $\psi \pmod{p}$ of order m . (Note that H does not depend on the choice of ψ .) Our formulation (3.1) does not quite agree with the statement in [16, Theorem 1]. This is because when $m = 2$, the factor $\eta(p)$ in [16, Theorem 1, p. 1159] should be corrected to read $\eta(p)^{a+1}$, which turns out to equal $\left(\frac{-D/p}{p}\right)^{r+1}$ in our notation.

For $z \in R_q^*$ and any characters $A, B \pmod{q}$, define another twisted hyper-Kloosterman sum $J(A, B, z)$ by

$$(3.3) \quad J(A, B, z) = \sum_{y_1, \dots, y_m \in R_q^*} A(y_1)B(y_1 \cdots y_m)\zeta_q^{y_1 + \cdots + y_m + z/(y_1 \cdots y_m)}.$$

In (3.11) below, we give a formula for $H(z)$ in terms of the sum $J(A, B, z)$ which is valid for $r \geq 2$. The sums $H(z)$ and $J(A, B, z)$ are special cases of the general twisted hyper-Kloosterman sum

$$K(A_1, \dots, A_m, z) := \sum_{x_1, \dots, x_m \in R_q^*} A_1(x_1) \cdots A_m(x_m)\zeta_q^{x_1 + \cdots + x_m + z/(x_1 \cdots x_m)},$$

which has been evaluated for $r \geq 2$ by Evans [5]. In the case $r = 1$, the sum $K(A_1, \dots, A_m, z)$ (as well as its analogue over general finite fields) was estimated by Katz [7, pp. 48–49]. When the characters A_1, \dots, A_m are all trivial, the sum $K(A_1, \dots, A_m, z)$ reduces to the familiar hyper-Kloosterman sum $J(1, 1, z)$, evaluated for $r \geq 2$ by Smith [14]. (Some errors in Smith’s formulations [14, Theorem 5] are corrected in [5].)

Using the Davenport-Hasse product formula (3.14), one can evaluate a sum related to $H(z)$ in the case $r = 1$, namely

$$\sum_{x_2, \dots, x_m \in R_p^*} \psi(x_2 x_3^2 \cdots x_m^{m-1})\zeta_p^{x_2 + \cdots + x_m + z/(x_2 \cdots x_m)};$$

see Duke [4], Katz [7, p. 85] for evaluations of this sum and its analogue over finite fields.

The following lemma expresses the Kloosterman sums $K(\eta, z), J(A, B, z)$, and $H(z)$ in terms of Gauss sums $G(\chi)$; cf. Katz [7, p. 47].

Lemma 3.1. *Let $z \in R_q^*$ and let A, B, η be characters \pmod{q} . Then*

$$(3.4) \quad K(\eta, z) = \frac{1}{\varphi(q)} \sum_{\chi} \bar{\chi}(z)G_1(\chi)G(\chi\eta)$$

(where χ runs through the $\varphi(q)$ characters \pmod{q}) and

$$(3.5) \quad J(A, B, z) = \frac{1}{\varphi(q)} \sum_{\chi} \bar{\chi}(z)G_1(\chi)G_1(\chi AB)G_1(\chi B)^{m-1}.$$

Also, if ψ is a character of order m (in which case $m|(p-1)$), then

$$(3.6) \quad H(z) = \frac{1}{\varphi(q)} \sum_{\chi} \bar{\chi}(z)G_1(\chi) \prod_{j=0}^{m-1} G_1(\chi\psi^j).$$

Proof. For $c \in R_q^*$,

$$\frac{1}{\varphi(q)} \sum_{\chi} \chi(c) = \begin{cases} 1, & \text{if } c = 1, \\ 0, & \text{if } c \neq 1. \end{cases}$$

Hence,

$$\begin{aligned} & \frac{1}{\varphi(q)} \sum_x \bar{\chi}(z) G_1(\chi) G(\chi\eta) \\ &= \frac{1}{\varphi(q)} \sum_x \bar{\chi}(z) \sum_{y \in R_q^*} \chi(y) \zeta_q^y \sum_{\alpha \in \mathcal{O}_q^*} \chi(N(\alpha)) \eta(N(\alpha)) \zeta_q^{T(\alpha)} \\ &= \sum_{\alpha \in \mathcal{O}_q^*} \eta(N(\alpha)) \zeta_q^{T(\alpha)+z/N(\alpha)} = K(\eta, z). \end{aligned}$$

This proves (3.4). The proofs of (3.5) and (3.6) are completely analogous. □

Theorem 3.2 below extends Ye’s evaluation (3.1) of $K(1, z)$ for $r \geq 2$ by showing that for any odd prime p , (3.1) holds for all (not necessarily prime) values of m dividing $p - 1$. More generally, for $r \geq 2$ and any prime $p \geq 2$, Theorem 3.2 gives an evaluation of $K(\eta, z)$ for all m (not necessarily prime or a divisor of $p - 1$), in terms of the sum J defined in (3.3). For evaluations of J , see [14], [5].

The case $r = 1$ will be considered in Theorem 3.3.

Theorem 3.2. *Let $r \geq 2$ and $z \in R_q^*$. Let η be any character (mod q) and let ϕ denote the Legendre symbol, viz., $\phi(x) = \left(\frac{x}{p}\right)$. Then*

$$(3.7) \quad K(\eta, z) = p^{(m-1)/2} \left(\frac{p}{m}\right)^r J(1, \eta, z), \quad \text{if } 2 \nmid m,$$

and

$$(3.8) \quad K(\eta, z) = p^{(m-1)/2} \left(\frac{m}{p}\right) \left(\frac{-Dp^{1-m}}{p}\right)^{r+1} \zeta_8^{(1-p)(1-m)} J(\phi, \eta, z), \quad \text{if } 2|m,$$

where $J(A, B, z)$ is defined by (3.3). Moreover, for every odd prime p and every m dividing $(p - 1)$, (3.1) holds.

Proof. If m is odd, then by (3.4) and (2.20),

$$\begin{aligned} K(\eta, z) &= p^{(m-1)/2} \left(\frac{p}{m}\right)^r \frac{1}{\varphi(q)} \sum_x \bar{\chi}(z) G_1(\chi) G_1(\chi\eta)^m \\ &= p^{(m-1)/2} \left(\frac{p}{m}\right)^r J(1, \eta, z), \end{aligned}$$

where the last equality follows from (3.5) with $A = 1, B = \eta$. This proves (3.7).

If m is even, then by (3.4) and (2.45),

$$\begin{aligned} K(\eta, z) &= p^{(m-1)/2} \left(\frac{-Dp^{1-m}}{p}\right)^{r+1} \left(\frac{m}{p}\right) \zeta_8^{(1-p)(1-m)} \frac{1}{\varphi(q)} \\ &\quad \times \sum_x \bar{\chi}(z) G_1(\chi) G_1(\chi\eta\phi) G_1(\chi\eta)^{m-1}. \end{aligned}$$

By (3.5) with $A = \phi, B = \eta$, this proves (3.8).

Next let p be an odd prime $\equiv 1 \pmod{m}$. It remains to prove (3.1).

Let ψ be a character (mod p) of order m and write $\chi = \xi^\nu$ as in (2.7). In view of (2.4) - (2.6), $\nu(\xi\psi^i) = 1$ for all i , so that by (2.3), $G_1(\xi\psi^i) = G_1(\xi)$ for all i . Thus

$$(3.9) \quad \prod_{i=0}^{m-1} G_1(\xi\psi^i) = G_1(\xi)^m.$$

Since $\nu = \nu(\chi)$ is relatively prime to $p - 1$, it follows that ν is relatively prime to m . Hence, applying σ_ν to both sides of (3.9), we obtain, by (2.8),

$$\prod_{i=0}^{m-1} G_1(\chi\psi^i) = \left(\frac{\nu}{p}\right)^{m-1} G_1(\chi)^m.$$

Thus, by (2.46),

$$(3.10) \quad \prod_{i=0}^{m-1} G_1(\chi\psi^i) = \begin{cases} G_1(\chi)^m, & \text{if } 2 \nmid m, \\ G_1(\chi)^{m-1}G_1(\chi\phi), & \text{if } 2|m. \end{cases}$$

Putting (3.10) in (3.6) and then using (3.5), we see that for $r \geq 2$,

$$(3.11) \quad H(z) = \begin{cases} J(1, 1, z), & \text{if } 2 \nmid m, \\ J(\phi, 1, z), & \text{if } 2|m. \end{cases}$$

Set $\eta = 1$ in (3.7) - (3.8) and make the substitution (3.11). Then using (2.36) for odd m and noting that $\left(\frac{p}{m}\right) = 1$ (since $p \equiv 1 \pmod{m}$), we obtain (3.1). □

For the remainder of this section, let $r = 1$. Then

$$K(\eta, z) = \sum_{\alpha \in \mathcal{O}_p^*} \eta(N(\alpha))\zeta_p^{T(\alpha)+z/N(\alpha)}.$$

By (2.11), we can write

$$\alpha = a + a_1\tau + \cdots + a_{m-1}\tau^{m-1} \quad (a \in R_p^*, a_i \in R_p).$$

Then $N(\alpha) = a^m$ and $T(\alpha) = ma$, so that

$$(3.12) \quad K(\eta, z) = p^{m-1} \sum_{a=1}^{p-1} \eta^m(a)\zeta_p^{ma+z/a^m}, \quad \text{when } r = 1.$$

In Theorem 3.3 below, we extend Ye's result (3.1) for $r = 1$ by showing that for any odd prime p , (3.1) holds for *all* m dividing $p - 1$.

We will need the product formula of Davenport-Hasse [2, Theorem 11.3.5, p. 355] for the Gauss sums

$$(3.13) \quad \gamma(\chi) := \sum_{a=1}^{p-1} \chi(a)\zeta_p^a,$$

namely,

$$(3.14) \quad \bar{\chi}^m(m)\gamma(\chi^m) = \prod_{j=0}^{m-1} \gamma(\chi\psi^j) / \prod_{j=1}^{m-1} \gamma(\psi^j),$$

where ψ is a character (mod p) of order m (so that $m|(p - 1)$). Note that $\gamma(\chi)$ is the Gauss sum $G_1(\chi)$ in the case $r = 1$. It is not difficult to show that for $p > 2$,

$$(3.15) \quad \prod_{j=1}^{m-1} \gamma(\psi^j) = p^{(m-1)/2} \left(\frac{m}{p}\right) \zeta_8^{(1-p)(m-1)};$$

see [2, p. 352]. Substituting (3.15) into (3.14), we obtain the following version of the Davenport-Hasse formula, when $p > 2$, $m|(p - 1)$:

$$(3.16) \quad \overline{\chi}^m(m)\gamma(\chi^m)p^{(m-1)/2} \left(\frac{m}{p}\right) \zeta_8^{(1-p)(m-1)} = \prod_{j=0}^{m-1} \gamma(\chi\psi^j).$$

Theorem 3.3. *Let $r = 1$ and $z \in R_p^*$, where p is an odd prime. Then (3.1) holds for every m dividing $(p - 1)$.*

Proof. Let ψ be a character (mod p) of order m . Since by (2.19),

$$G(\chi) = p^{m-1}\overline{\chi}^m(m)\gamma(\chi^m),$$

it follows from (3.16) that

$$(3.17) \quad G(\chi) = p^{(m-1)/2} \left(\frac{m}{p}\right) \zeta_8^{(1-p)(1-m)} \prod_{j=0}^{m-1} \gamma(\chi\psi^j).$$

Substituting (3.17) into (3.4) with $\eta = 1$, we obtain

$$(3.18) \quad K(z) = p^{(m-1)/2} \left(\frac{m}{p}\right) \zeta_8^{(1-p)(1-m)} H(z),$$

by (3.6). This completes the proof, as (3.18) is the same as (3.1) in the case $r = 1$. □

4. A PRODUCT FORMULA FOR GAUSS SUMS $G(\chi)$

In Theorem 4.1 below, we give a product formula for the Gauss sums $G(\chi)$, which in the case $m = r = 1$ reduces to the Davenport-Hasse product formula (3.16).

Theorem 4.1. *Let p be an odd prime and let ψ be a character (mod p) of order ℓ (so that $\ell|(p - 1)$). Let χ be any character (mod q). Then if $r \geq 2$,*

$$(4.1) \quad \overline{\chi}^{\ell m}(\ell)G(\chi^\ell)p^{(\ell-1)(rm+m-1)/2}C(\chi) = \prod_{j=0}^{\ell-1} G(\chi\psi^j),$$

where $C(\chi) \in \{\pm 1, \pm i\}$ is defined by

$$(4.2) \quad C(\chi) := \begin{cases} \left(\frac{\nu(\chi)}{p}\right)^{\ell-1}, & \text{if } 2 \nmid m, 2|r, \\ \zeta_8^{(1-p)(\ell-1)} \left(\frac{\ell}{p}\right) \left(\frac{m}{p}\right)^{\ell-1} \left(\frac{\nu(\chi)}{p}\right)^{(\ell-1)(m-1)}, & \text{if } 2 \nmid r, \\ \zeta_8^{(1-p)(1-m)(\ell-1)} \left(\frac{\ell}{p}\right) \left(\frac{m}{p}\right)^{\ell-1} \left(\frac{-Dp^{1-m}}{p}\right)^{\ell-1} \left(\frac{\nu(\chi)}{p}\right)^{\ell-1}, & \text{if } 2|m, 2|r, \end{cases}$$

with $\nu(\chi)$ defined by (2.4) and (2.6). If in the case $r = 1$, we define the (previously undefined) expression $\nu(\chi)$ by setting $\nu(\chi) = 1$, then (4.1) also holds when $r = 1$, provided that $(m, \ell) = 1$.

Proof. We first consider the case $r \geq 2$. If χ is nonprimitive, then both sides of (4.1) vanish by Theorem 2.2. Assume therefore that χ is primitive.

First suppose that χ is normalized, i.e., $\nu(\chi) = 1$. In this case $\chi\psi^j$ is normalized, i.e., $\nu(\chi\psi^j) = 1$, for each j . Hence by (2.20) and (2.3),

$$(4.3) \quad G(\chi) = G(\chi\psi^j), \quad \text{for all } j.$$

Choose b relatively prime to $q(p - 1)$ such that $b \equiv \ell \pmod{q}$, and define c by $bc \equiv 1 \pmod{q(p - 1)}$. We claim that

$$(4.4) \quad \sum_{\alpha \in \mathcal{O}_q^*} \chi^b(N(\alpha))\zeta_q^{T(\alpha b)} = \sum_{\alpha \in \mathcal{O}_q^*} \chi^\ell(N(\alpha))\zeta_q^{T(\alpha \ell)}.$$

To verify (4.4), apply σ_c to both sides to obtain $G(\chi)$ on the left and $G(\chi^{c\ell})$ on the right; then note that $\nu(\chi) = \nu(\chi^{c\ell}) = 1$, so that $G(\chi) = G(\chi^{c\ell})$ by (2.20) and (2.3).

We can rewrite (4.4) as

$$(4.5) \quad \sigma_b G(\chi) = \bar{\chi}^{\ell m}(\ell)G(\chi^\ell).$$

In view of (4.3) and (4.5), the proposed equality (4.1) is equivalent to

$$(4.6) \quad \sigma_b(G(\chi))p^{(\ell-1)(rm+m-1)/2}C(\chi) = G(\chi)^\ell.$$

By (2.42) and by (2.44) with $\nu = b$, the left side of (4.6) equals

$$\sigma_b(G_1(\chi)^m) \left(\frac{\ell}{p}\right)^{m+1} A(m)p^{(\ell-1)(rm+m-1)/2}C(\chi),$$

while the right side of (4.6) equals

$$G_1(\chi)^{m\ell}A(m)^\ell.$$

Thus (4.6) (and hence (4.1)) is equivalent to

$$(4.7) \quad C(\chi) = A(m)^{\ell-1} \left(\frac{\ell}{p}\right)^{m+1} p^{(1-\ell)(rm+m-1)/2}G_1(\chi)^{m\ell}/\sigma_b(G_1(\chi)^m).$$

Substitute the value of $G_1(\chi)$ given by (2.3) into (4.7) to see, after a tedious calculation, that (4.7) is equivalent to (4.2) when $\nu(\chi) = 1$. This completes the proof of (4.1) for $r \geq 2$ when $\nu(\chi) = 1$. To prove (4.1) for $r \geq 2$ and general $\nu(\chi)$, first write down (4.1) with ξ in place of χ (in the notation of (2.7)). Then, applying σ_ν to both sides, we obtain (4.1). This completes the proof of the theorem in the case $r \geq 2$.

Now let $r = 1$ and assume that $(m, \ell) = 1$. It remains to prove

$$(4.8) \quad \bar{\chi}^{\ell m}(\ell)G(\chi^\ell)p^{(\ell-1)(m-1/2)}C = \prod_{j=0}^{\ell-1} G(\chi\psi^j),$$

where

$$(4.9) \quad C = \zeta_8^{(1-p)(\ell-1)} \left(\frac{\ell}{p}\right) \left(\frac{m}{p}\right)^{\ell-1}.$$

Since, by (2.19),

$$G(\chi) = \bar{\chi}^m(m)p^{m-1}\gamma(\chi^m)$$

for every character $\chi \pmod{p}$, we have in particular,

$$(4.10) \quad G(\chi\psi^j) = \bar{\chi}^m(m)\bar{\psi}^m(m)^{mj}p^{m-1}\gamma(\chi^m\psi^{mj})$$

for all j , and

$$(4.11) \quad \bar{\chi}^{\ell m}(\ell)G(\chi^\ell) = \bar{\chi}^{\ell m}(\ell m)p^{m-1}\gamma(\chi^{m\ell}).$$

Because $(m, \ell) = 1$, it follows that ψ^{mj} runs through the same characters as ψ^j does when j runs through $0, 1, 2, \dots, \ell - 1$. Thus, by (4.10),

$$(4.12) \quad \prod_{j=0}^{\ell-1} G(\chi\psi^j) = \bar{\chi}^{m\ell}(m)p^{\ell(m-1)} \left(\frac{m}{p}\right)^{\ell-1} \prod_{j=0}^{\ell-1} \gamma(\chi^m\psi^j).$$

By (3.16) with $m = \ell$,

$$(4.13) \quad \prod_{j=0}^{\ell-1} \gamma(\chi^m\psi^j) = \bar{\chi}^{m\ell}(\ell)p^{(\ell-1)/2}\gamma(\chi^{m\ell}) \left(\frac{\ell}{p}\right) \zeta_8^{(1-p)(\ell-1)}.$$

Multiplying (4.13) by (4.12) and then dividing the resulting equality by (4.11), we obtain (4.8). \square

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