BEHAVIOUR OF FUNCTION FIELD GAUSS SUMS AT INFINITY

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(WITH AN APPENDIX BY JOSÉ FELIPE VOLOCH)

ABSTRACT

We describe the valuations of the function field Gauss sums at the infinite places, by relating them to Weierstrass gaps. This generalizes our previous results for $\mathbf{F}_q[T]$, in which case the valuations are all $-1/(q-1)$, in direct analogy with the well-known classical result that all the absolute values of Gauss sums are $q^{1/2}$. We also investigate the sign of quadratic or higher-order Gauss sums, giving results in the direction of Gauss' sign theorem and the work of Cassels and Matthews.

Introduction

An analogue of Gauss sums taking values in function fields over finite fields was introduced and studied in [**8**, **9**, **10**, **12**]. In [**8**, **9**], analogues of various classical results about Gauss sums such as Stickelberger factorization, Hasse–Davenport and Gross–Koblitz results were established, in the case of $\mathbf{F}_q[T]$. The general case turns out to be interestingly different, in view of the established analogies, and is discussed in [**10**, **12**]. More relevant to this paper is another well-known classical fact that the absolute value of a Gauss sum at any infinite place is $q^{1/2}$. For the $\mathbf{F}_q[T]$ analogue, it was shown in [**8**, **9**] that the valuation at any infinite place is $-1/(q-1)$. Here 2 and $q-1$ can be described as the cardinalities of $\mathbf{Z}^*$ and $\mathbf{F}_q[T]^*$ respectively, or as the degrees of respective cyclotomic fields over their maximal 'totally real' subfields. We shall see (Theorem 1.8) that even though these analogies generalize, the valuation in the general case is closely related to Weierstrass gaps.

We deal only with the case where the infinite place is of degree one. It might be worthwhile to consider the general case, and the interested reader will find the relevant cyclotomic theory developed in [**5**]. For the general case, when the genus is zero, see [**10**, **12**].

Next we consider the question of the sign of Gauss sums and establish (Theorem 2.5) an analogue of Gauss' theorem on the sign of quadratic Gauss sums. Then we consider signs of mth-order Gauss sums, in the spirit of the investigations of Cassels and Matthews (see [**7**]).

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to thank Greg Anderson for asking me about the signs and directing me to papers of Matthews. He has also computed the valuation of Gauss sums for generic primes, by using his theory of Baker functions in characteristic p.

0. *Background*

Notation

$\mathbf{F}_q$: a finite field of characteristic p containing q elements
K: a function field of one variable with the field of constants $\mathbf{F}_q$
∞: a place of K of degree one
H: maximal abelian unramified extension of K split at ∞
A: the ring of elements of K with no poles outside ∞
$\mathfrak{p}$: a prime of A of degree d
K_∞: the completion of K at ∞
Ω: the completion of an algebraic closure of K_∞
h: the class number of K
$\underline{g}$: the genus of K

Drinfeld modules, Gauss sums (see **[2, 4, 10]** for more details)

0.1 Fix a local parameter t^{-1} at ∞. For $x \in K_\infty^*$, define $\deg(x) \in \mathbf{Z}$ and $\operatorname{sgn}(x) \in \mathbf{F}_q^*$ to be the exponent in the highest power of t and the coefficient of the highest power, respectively, in the expansion of x as a Laurent series in t^{-1}, with coefficients in $\mathbf{F}_q$.

0.2 Let L be a field containing A and let $L\{F\}$ denote the noncommutative ring generated by the elements of L and by a symbol F, with the commutation relation $Fl = l^q F$, for all $l \in L$. By a Drinfeld A-module ρ over L (in fact, 'sgn-normalized, of rank one and generic characteristic', but we shall drop these words) we mean an injective homomorphism $\rho: A \to L\{F\}$ $(a \in A \mapsto \rho_a \in L\{F\})$ such that, for all $a \in A - \{0\}$,

$$\rho_a = \sum_{i=0}^{\deg(a)} \rho_{a,i} F^i, \quad \rho_{a,i} \in L, \quad \rho_{a,0} = a, \quad \rho_{a,\deg(a)} = \operatorname{sgn}(a).$$

Two Drinfeld A-modules $\rho, \tilde{\rho}$ are considered isomorphic (say over $L' \supset L$) if there is a nonzero $l' \in L'$ such that $l'\rho_a = \tilde{\rho}_a l'$ for $a \in A$.

0.3 Minimal L such that a Drinfeld A-module over L exists is H up to isomorphism. Note that the degree of the extension H of K is h. There are h nonisomorphic Drinfeld A-modules over H, Galois conjugates over K to each other.

0.4 For a Drinfeld module ρ over K_∞, define the exponential $e(z) = e_\rho(z)$ of ρ as the power series characterized by $e(az) = \rho_a(e(z))$, for all $a \in A$ and $e(z) = z +$ higher-order terms in z. Then $e(z)$ is everywhere convergent in Ω; it has coefficients in H. The kernel of the function e is a rank one A-lattice in Ω and hence can be described as $\tilde{\pi}_{\mathscr{A}} \mathscr{A}$, for some $\tilde{\pi} = \tilde{\pi}_{\mathscr{A}} \in \Omega$ and an ideal $\mathscr{A}$ of A. The fundamental period $\tilde{\pi}$ (in fact, it has been defined only up to multiplication by elements in $\mathbf{F}_q^*$) of $e(z)$ can be thought of as an analogue of $2\pi i$ and is known to be transcendental **[13]**. We have $\tilde{\pi}^{q-1} \in K_\infty$, just as $(2\pi i)^2 \in \mathbf{R}$. The nonarchimedean nature of Ω then gives the product formula $e(z) = z \prod (1 + z/\lambda)$, where the product runs over the nonzero elements λ of the lattice $\tilde{\pi}\mathscr{A}$.

0.5 Let $\bar{L}$ be an algebraic closure of L. For $a \in A$, define 'a-torsion of ρ' as

$\Lambda_a := \{u \in \bar{L}: \rho_a(u) = 0\}$. For an ideal I of A, we define 'I-torsion of ρ' as $\Lambda_I := \{u \in \bar{L}: \rho_i(u) = 0, \text{ for all } i \in I\}$. It is an A-module under ρ. By adjoining Λ_I (I nonzero) to K, we obtain another type of cyclotomic extension of K. In analogy with the classical case, $K(\Lambda_I) = H(\Lambda_I)$ has Galois group $(A/I)^*$ over H, and the decomposition (also inertia) group at an infinite place of H is $\mathbf{F}_q^* \subset (A/I)^*$. Hence the degree of $H(\Lambda_I)$ over its 'maximal totally real' subfield $H(\Lambda_I)^+$ is $q-1$.

0.6 Let $\mathfrak{p}$ be a prime of A of degree d. Choose an A-module isomorphism $\psi: A/\mathfrak{p} \to \Lambda_{\mathfrak{p}}$ (an analogue of additive character) and let χ_j ($j \bmod d$) be $\mathbf{F}_q$-homomorphisms $A/\mathfrak{p} \to L$, where L is a field containing $K(\Lambda_{\mathfrak{p}})$, indexed so that $\chi_j^q = \chi_{j+1}$ (special multiplicative characters which are q^j-powers of 'Teichmüller character', say χ_0). Then we define the Gauss sums

$$g_j := g(\chi_j) := -\sum_{z \in (A/\mathfrak{p})^*} \chi_j(z^{-1})\, \psi(z).$$

1. *Valuations at* ∞

1.1 Let ρ be a Drinfeld module over K_∞ with the corresponding lattice $\tilde{\pi}\mathscr{A}$. Let $\mathfrak{p}$ be a prime of A of degree d. Consider the Gauss sums as defined in 0.6. Note that $\Lambda_{\mathfrak{p}} = \{e(\tilde{\pi}r): r \in \mathfrak{p}^{-1}\mathscr{A}\}$ and that $g_j \in \tilde{\pi}\mathbf{F}_{q^d}((t^{-1}))$.

THEOREM 1.2. *The degree of the Gauss sum is same as the maximum possible degree of a* $\mathfrak{p}$*-torsion element.*

Proof. Let $R \subset \mathfrak{p}^{-1}\mathscr{A}$ be a set of representatives modulo $\mathscr{A}$ of the lowest possible degrees. It is easy to see that there is an $\mathbf{F}_q$-basis $\{r_1, \ldots, r_d\}$ of R such that $\{r_1 + r_2\theta_2 + \ldots + r_d\theta_d : \theta_i \in \mathbf{F}_q\}$ is exactly the subset of monic (that is, of sign 1) elements of R of maximal degree.

We can assume that the torsion points $\psi(r)$ are just $e(\tilde{\pi}r)$, for $r \in R$. The product formula in 0.4 shows that the degree of $\psi(r)$ is maximal when the degree of r is maximal. Now, ψ being additive, the maximal degree is the degree of $\psi(r_1)$. It is enough to show that this top degree does not get cancelled in the summation. Since both ψ and χ_j are $\mathbf{F}_q$-linear, and $q-1 = -1$ in characteristic p, we have $g_j = \sum \chi_j(z^{-1})\, \psi(z)$, where now the sum is taken over the monic representatives of $\mathfrak{p}^{-1}\mathscr{A}/\mathscr{A}$. If we note that $\chi_j(r_i)$ is a basis of $\mathbf{F}_{q^d}$ over $\mathbf{F}_q$, the theorem then follows from the following lemma.

LEMMA 1.3. *If* $f_1, \ldots, f_d$ *is a basis of* $\mathbf{F}_{q^d}$ *over* $\mathbf{F}_q$, *then*

$$\Sigma := \sum_{\theta_i \in \mathbf{F}_q} \frac{1}{f_1 + f_2\theta_2 + \ldots + f_d\theta_d} \neq 0.$$

Proof. Let

$$M(x_1, \ldots, x_k) := \prod_{j=1}^{k} \prod_{\theta_i \in \mathbf{F}_q} (x_j + x_{j+1}\theta_{j+1} + \ldots + x_k\theta_k).$$

Then with $P(t) := \prod (t + f_2\theta_2 + \ldots + f_d\theta_d)$, where the product is over all $\theta_i \in \mathbf{F}_q$, we have $\Sigma = P'(f_1)/P(f_1)$ and $P(f_1) = M(f_1, \ldots, f_d)/M(f_2, \ldots, f_d)$. As $P(t)$ is an $\mathbf{F}_q$-linear polynomial, $P'(t)$ is just the coefficient of t in $P(t)$ and hence equals $\prod (f_2\theta_2 + \ldots + f_d\theta_d)$, where now the product runs through $\theta_i \in \mathbf{F}_q$ not all zero. But this is just

$(-1)^{d-1}M(f_2,\ldots,f_d)^{q-1}$, because $\prod_{\theta\in\mathbf{F}_q^*}\theta=-1$ and $(-1)^{(q^{d-1}-1)/(q-1)}=(-1)^{d-1}$. Hence $\Sigma=(-1)^{d-1}M(f_2,\ldots,f_d)^q/M(f_1,\ldots,f_d)$ is nonzero, as it is the product of terms which are nonzero because the f_i are linearly independent over $\mathbf{F}_q$. This finishes the proof of the lemma and of the theorem.

DEFINITION 1.4. Let $0\leqslant n_1<n_2<\ldots<n_g$ be the integers n ('gaps of $\mathscr{A}$') so that there are no elements of $\mathscr{A}$ of degree n. (Here g is just the number of gaps. It is the genus $\underline{g}$ when $\mathscr{A}=A$, by Riemann–Roch. Note that n_g-g is an ideal class invariant, and hence when $g=0$ we take $n_0=-1$ to retain this property.) Call $\mathfrak{p}$ exceptional with respect to $\mathscr{A}$ (or, rather, its ideal class) if n_g is a gap for the fractional ideal $\mathfrak{p}^{-1}\mathscr{A}$ (that is, there is no element of degree n_g in $\mathfrak{p}^{-1}\mathscr{A}$). We say that $\mathfrak{p}$ is exceptional if it is exceptional with respect to some $\mathscr{A}$.

THEOREM 1.5. (1) *Principal primes are not exceptional.* (2) *Primes of degree more than $\underline{g}$ are not exceptional. In particular, there are at most finitely many exceptional primes.* (3) *Primes of degree one which are not principal are exceptional.*

Proof. Let $\mathfrak{p}$ be a prime of degree d. Since n_g is the largest gap of $\mathscr{A}$, there is an element, say $e\in\mathscr{A}$, of degree n_g+d. If $\mathfrak{p}$ is principal, $\mathfrak{p}=(P)$ say, then $e/P\in\mathfrak{p}^{-1}\mathscr{A}$ has degree n_g and (1) follows. In general, given $\mathfrak{p}$, let d' be the degree of the smallest degree element in the smallest degree ideal $\bar{\mathfrak{p}}$ in the ideal class inverse to that of $\mathfrak{p}$. Counting the gaps of $\bar{\mathfrak{p}}$, we see that $d'\leqslant\deg\bar{\mathfrak{p}}+\underline{g}$. If $d>d'-\deg\bar{\mathfrak{p}}$, then $\mathfrak{p}^{-1}$ has an element of negative degree, and just as above we see that $\mathfrak{p}$ in that case cannot be exceptional. (2) follows. Now let $\mathfrak{p}$ be of degree one and not principal (equivalently, $\underline{g}\neq 0$). Then 0 is a gap for $\mathfrak{p}$, but not for A. Hence the count of gaps shows that the largest gap for A is also the largest gap for $\mathfrak{p}$, and hence $\mathfrak{p}$ is exceptional for $\mathscr{A}=\mathfrak{p}$. This proves (3) and hence the theorem.

REMARKS 1.6. (i) If $\mathfrak{p}$ is a nonprincipal prime of the lowest possible degree for A for a hyperelliptic K, then $\mathfrak{p}$ has $2\underline{g}-1$ as a gap and hence is exceptional for $\mathscr{A}=\mathfrak{p}$.

(ii) When $\underline{g}=1$, the theorem shows that the exceptional primes are exactly the primes of degree one and are hence $h-1$ in number.

(iii) By Theorem 1.5, there are no exceptional primes when $h=1$. (By [6], apart from $A=\mathbf{F}_q[T]$ (one for each q), there are only four such A.) On the other hand, Voloch (see the Appendix) has given a nice characterization of exceptional primes and proved that they do exist when $h>1$.

LEMMA 1.7. *If $\mathfrak{p}$ is (respectively is not) exceptional, the highest degree element in R has degree less than (respectively equal to) n_g.*

Proof. If $\mathfrak{p}$ is not exceptional, $\mathfrak{p}^{-1}\mathscr{A}$ has an element of degree n_g, which is not congruent to any element of lower degree modulo $\mathscr{A}$, since n_g is a gap for $\mathscr{A}$. On the other hand, any element of $\mathfrak{p}^{-1}\mathscr{A}$ of degree more than n_g is congruent modulo $\mathscr{A}$ to one of lower degree, as can be seen by subtracting an element of same degree (which exists, as n_g is the largest gap) and opposite sign.

Now we state the main theorem of this section.

THEOREM 1.8. *Let ρ be a Drinfeld module over H. Let $i_k: H \hookrightarrow K_\infty$ be the embedding corresponding to an infinite place ∞_k of H and $\tilde{\pi}\mathscr{A}$ be the corresponding lattice. Then (with the notation as in Definition* 1.4) *the degree of the Gauss sum is the same at any prime above ∞_k and is less than or equal to $q^{n_g-g+1}/(q-1)$, with equality if and only if $\mathfrak{p}$ is not exceptional with respect to $\mathscr{A}$.*

Proof. Let $n(i)$ be the number of monic elements of $\mathscr{A}$ of degree i. Then it is easy to see that $n(i)$ is q^{i-j}, if $n_j < i < n_{j+1}$, where for convenience we take $n_{g+1} = \infty$. Then by [**11**, p. 41], the degree of $\tilde{\pi}$ is (the sum is p-adic) $\sum (q-1)\,in(i) = \Sigma_1 + \Sigma_2$, where Σ_1 is the sum over $i \leqslant n_g$ and Σ_2 over $i > n_g$. Then

$$\Sigma_2 = (q-1)\sum_{k=1}^{\infty}(n_g+k)\,q^{n_g+k-g} = -(n_g+1)\,q^{n_g-g+1} + \frac{q^{n_g-g+2}}{q-1}.$$

By Theorem 1.2 the degree of the Gauss sum is the degree of $e(\tilde{\pi}r_1) = \tilde{\pi}r_1\prod(1+r_1/a)$, where the product runs over nonzero $a \in \mathscr{A}$. Let us compute the degree of $r_1\prod(1+r_1/a)$. Note that there are no terms of negative degree in the product, by the choice of R. It is clearly sufficient to consider only the case where $\mathfrak{p}$ is not exceptional. Then the degree is easily seen to be

$$n_g + \sum_{i \neq n_j,\, i \leqslant n_g} (n_g - i)(q-1)\,n(i) = n_g[1 + \sum (q-1)\,n(i)] - \sum (q-1)\,in(i).$$

Now the sum in the bracket telescopes to q^{n_g-g+1} by the determination of $n(i)$ above. Combining with the formula for the degree of $\tilde{\pi}$, the degree of the Gauss sum then turns out to be $-q^{n_g-g+1} + q^{n_g-g+2}/(q-1) = q^{n_g-g+1}/(q-1)$, as claimed. This proves the theorem.

REMARK 1.9. Let D be the degree of a nonprincipal prime of A of smallest possible degree. If the largest gap for A is smaller than $D+\underline{g}-1$ (for example, $D > 1$ and A with gaps 1 to $\underline{g}$), then $\mathfrak{p}$ is not exceptional for $\mathscr{A} = \mathfrak{p}$ and hence for such A, every prime has 'generic' infinite valuation for at least one ∞_k, by the theorem. The situation when A has a gap $2\underline{g}-1$ gives another example of this, since then there are no exceptional primes for $\mathscr{A} = A$: the largest gap for $\mathfrak{p}^{h-1}$ is $\leqslant 2\underline{g}-1+(h-1)\,d$, and hence the largest gap for $\mathfrak{p}^{-1}$ is $\leqslant 2\underline{g}-1-d$. In fact, for general A, Voloch (see the Appendix) shows how to find $\mathscr{A}$ with no exceptional primes with respect to it.

2. *Sign of the Gauss sum*

2.1 In this section, we restrict to the case $A = \mathbf{F}_q[T]$, with T of sign one. Then $\rho_T = T + F$. We begin by explaining what mth-order Gauss sum, when m divides q^d-1, means in our context. For $y \in (q^d-1)^{-1}\mathbf{Z}/\mathbf{Z} - \{0\}$, let us write $0 < (q^d-1)\,y = \sum y_j q^j < q^d-1$, with $0 \leqslant y_j < q$. Then we put $g(y) = \prod g_j^{y_j}$. Note that $g(q^j/(q^d-1)) = g_j$ corresponds to the multiplicative characters χ_j of order q^d-1. Hence it is natural to consider the reduced denominator of y as the order of the Gauss sum. (For more explanation, see [**8**, **9**].) In particular, if $p \neq 2$, we can talk about the 'quadratic Gauss sum' $g(1/2) = \prod g_j^{(q-1)/2}$. Also, $g(y)\,g(1-y) = \prod g_j^{q-1} = (-1)^d\mathfrak{p}$ (here and below $\mathfrak{p}$ will be assumed to be monic) can be thought of as an analogue of the well-known classical fact $g(\chi)\,g(\bar{\chi}) = \chi(-1)\,q$ (see [**8**]).

2.2 We can consider g_j as an element of $\tilde{\pi}K_\infty(\zeta_{q^d-1})$ and can talk about its 'sign' sgn. Carlitz [1] (but see [11, pp. 33, 42] for our normalizations) gives a formula for $\tilde{\pi}$, which implies that $\tilde{\pi}^{q-1} \in K_\infty$ and $\operatorname{sgn}(\tilde{\pi}^{q-1}) = -1$. We write $\varepsilon := \operatorname{sgn}(\tilde{\pi})$ and $t_j := \chi_j(T)$. Here j is considered modulo d. We first give a formula for $\operatorname{sgn}(g_j)$ in terms of ε and the t_i.

THEOREM 2.3. *We have*

$$\operatorname{sgn}(g_j) = (-1)^{d-1}\varepsilon \prod_{k=1}^{d-1} (t_k - t_0)^{-q^j}.$$

Proof. Consider the $\mathbf{F}_q$-basis $r_i := T^{d-i}$, $0 < i \leqslant d$, for the representatives of $A/\not{p}$. Then Theorem 1.2 shows that $\operatorname{sgn}(g_j)$ is ε times $\chi_j(\Sigma)$, where $\Sigma := \sum_{\theta_i \in \mathbf{F}_q} (r_1 + r_2\theta_2 + \ldots + r_d\theta_d)^{-1}$. By [1, Theorem 9.4] (there are some sign mistakes in the theorem and proof, but these are easily correctable), we have $\Sigma = (-1)^{d-1}/\prod (T^{q^k} - T)$, where k runs through $1 \leqslant k < d$. This proves the theorem.

2.4 Now, in general, as can be easily seen from this theorem, the dependence of the $\operatorname{sgn}(g_j)$ or even $\operatorname{sgn}(g(1/m))$ on $\not{p}$ is quite complicated and not just through d. But when $m = 2$, that is, the case of quadratic Gauss sums, we have the following analogue of Gauss' theorem.

THEOREM 2.5. *Let* $i := \varepsilon^{(q-1)/2}$. (*Note* $i^2 = -1$.) *Then* $s_2 := \operatorname{sgn}(g(1/2))$ *depends only on the congruence class of* q *and* d *modulo* 4. *In fact, we have*

$$s_2 = (-i)^{d+2} \quad (q \equiv 1 \bmod 4), \quad s_2 = (-i)^{d^2+2} \quad (q \equiv 3 \bmod 4).$$

In other words, s_2 *is* i, $(-1)^{(q-1)/2}$, $(-i)(-1)^{(q-1)/2}$ *or* -1 *according as* d *is congruent to* 1, 2, 3 *or* 4 *modulo* 4.

Proof. (We know by 2.1 that $g(1/2)^2 = (-1)^d \not{p}$ and hence s_2 is a fourth root of unity, *a priori*.) By Theorem 2.3 and the formula for $g(1/2)$ in 2.1, we see that $s_2 = i^d \prod (t_k - t_0)^{-(q^d-1)/2}$, with $0 < k < d$. Now $(q^d-1)/2 = (q^{d-1} + \ldots + q + 1)(q-1)/2$. Since $t_k^{q^r} = t_{k+r}$, we have

$$\prod (t_k - t_0)^{q^{d-1}+\ldots+1} = \prod (t_j - t_i) = (-1)^{d(d-1)/2} \prod (t_j - t_i)^2, \qquad (**)$$

where $d > j \neq i \geqslant 0$ in the second product and $d > j > i \geqslant 0$ in the third. On the other hand,

$$\prod_{j>i} (t_j - t_i)^{q-1} = \frac{\prod_{j>i} (t_{j+1} - t_{i+1})}{\prod_{j>i} (t_j - t_i)} = (-1)^{d-1},$$

where the last equality follows from the fact that there are $d-1$ reversals of the sign, namely when $j = d-1$. (Alternatively: the 'discriminant' is square exactly when d is odd.) Putting this together, we see that $s_2 = i^d(-1)^{d(d-1)(q-1)/4}(-1)^{d-1}$, which is equivalent to the formulae claimed. This proves the theorem.

2.6 Now we turn to the question of sign, say s_m, of the mth-order Gauss sum $g(1/m)$, when $m > 2$. Theorem 2.3 provides a formula. Now, for the classical Gauss

sums, Matthews [7] has given some interesting formulae when $m = 3$ or 4, in terms of '$1/m$th residue set', factorials and torsion values of elliptic functions. Theorems 2.7 and 2.10 provide rough analogues of these formulae, when m divides q^2-1. Note that $\mathbf{Q}(\zeta_3)$ and $\mathbf{Q}(\zeta_4)$ are quadratic cyclotomic extensions of $\mathbf{Q}$, whereas $K(\zeta_{q^2-1})$ is a quadratic cyclotomic extension of K. Results with the weaker condition that m divides q^d-1 would be more desirable. In our situation we do have 'complex multiplication' as in [7], and the exponential for $\mathbf{F}_{q^d}[T]$ seems to be a good function in the place of elliptic functions of [7], but we have not been able to make a stronger analogy. On the other hand, in the general case, our formulae can be considered to be in the spirit of Patterson's simplification (see [7]) of Matthews' formulae. For history of the subject, various analogies and comparison of complexities of different formulae, see [7].

Let S be a '$1/(q-1)$th residue set modulo $\mathfrak{p}$', that is, a set of representatives of $(A/\mathfrak{p})^*/\mathbf{F}_q^*$. Define $\alpha(S)\in\mathbf{F}_{q^d}^*$ by $\alpha(S)\equiv\prod_{s\in S}s \bmod \mathfrak{p}$. Then by $\mathbf{F}_q$-linearity of $e(z)$, $\mu := \prod_{s\in S} e(s\pi/\mathfrak{p})/\alpha(S)$ is independent of the choice of S. Then it is easy to see, from the fact that the product of all nonzero $\mathfrak{p}$-torsion points is $\mathfrak{p}$, that $g(1/(q-1))^{q-1} = (-1)^d\mathfrak{p} = -\mu^{q-1}$.

THEOREM 2.7. *We have*

$$s_{q-1} = (-1)^{d(d-1)/2}\,\varepsilon^{-d}\,\mathrm{sgn}\,(\mu)^2.$$

Proof. By Theorem 2.3 and (**), we have $s_{q-1} = (-1)^{d(d-1)/2}\varepsilon^d\prod(t_j-t_i)^{-2}$, where the product is over $d>j>i\geqslant 0$. Hence it is enough to show that $\mathrm{sgn}\,(\mu) = \varepsilon^{(q^d-1)/(q-1)}\prod(t_j-t_i)^{-1}$. We can choose S to be the set of all monic elements of A of degree less than d. Let D_j denote the product of all monic elements of A of degree j. Then it is enough to show that $\chi_0(D_{d-1}\dots D_1D_0) = \prod(t_j-t_i)$. Now $D_j = \prod_{i<j}(T^{q^j}-T^{q^i})$, by [1, p. 140]. The claim and the theorem now follow easily.

REMARK 2.8. Let m divide $q-1$. Choose a set S_0 of representatives for $\mathbf{F}_q^*/\langle\zeta_m\rangle$ and let S' be $1/m$th residue set. We can choose S' to consist of elements of degree less than d and with signs in S_0. Let μ' be defined in analogous fashion to μ with S' in place of S. Then $\mathrm{sgn}\,(\mu') = \mathrm{sgn}\,(\mu)^{(q-1)/m}$ and $s_m = s_{q-1}^{(q-1)/m}$. Hence the theorem provides a similar formula for s_m.

2.9 Now consider m dividing q^2-1. As in Remark 2.8, it is enough to consider $m = q^2-1$. Let $\mathfrak{p}$ be such that the norm of $\mathfrak{p}$ (that is, q^d) is congruent to one modulo m, so that d is even and $\mathfrak{p}$ splits in $B := \mathbf{F}_{q^2}[T]$ as say $\mathfrak{p} = \mathfrak{p}_1\mathfrak{p}_2$. We identify $(A/\mathfrak{p})^*$ with $(B/\mathfrak{p}_1)^*$. By Theorem 2.3, ignoring the explicit powers of -1 and ε, the interesting part of s_{q^2-1} is $\mathscr{S} := \prod(t_j-t_0)^{(q^d-1)/(q^2-1)}$. Let $\alpha_1 := \prod(t_j-t_i)$, where the product runs through $d>j>i\geqslant 0$, and let $\alpha_2 := \prod(t_j-t_i)$, where the product runs through $d>j>i\geqslant 0$ and i,j are even. Then α_1 and α_2 are $\alpha(S)$ for S as in 2.6 for α_1, but for S corresponding to B and $\mathfrak{p}_1$ in place of A and $\mathfrak{p}$ for α_2.

THEOREM 2.10. *We have* $\mathscr{S} = \alpha_2^{1-q}\alpha_1$.

Proof. It is easy to see that $\mathscr{S} = \prod(t_j-t_i)$, where i is even and $j\neq i$. Decomposing the product over $i>j$ and $i<j$, we see that $\mathscr{S} = \alpha_2\prod(t_j-t_i)$, where now the product is over $j>i$ and at least one of i and j is even. But then this product is α_1/α_2^q, and hence the theorem is established.

REMARK 2.11. By [1, p. 148], the sum Σ in the proof of Theorem 2.3 can also be expressed as $(-1)^{d-1}\Pi(q^{d-1}-1)/\Pi(q^{d-1})$, where Π is Carlitz' factorial (see [1, 11]). This gives a simple expression for the sign of Gauss sums in terms of Carlitz factorials.

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