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Thus

$$\eta^n = \frac{\chi^{ln}(l)\, G_{fn}(\chi^\delta)}{G_{fn}(\chi^{\delta l})} \prod_{j=1}^{l-1} \frac{G_{fn}(\chi^\delta \psi^j)}{G_{fn}(\psi^j)}. \tag{9}$$

Since $n \equiv \delta \pmod{q-1}$, $\chi^{ln}(l) = \chi^{\delta l}(l)$. Therefore, by (7), the right side of (9) equals 1, so

$$\eta^n = 1. \tag{10}$$

By the definition of η and of Gauss sums,

$$\eta^l \equiv \frac{\chi^{l^2}(l)\, \bar{\chi}^l(l)\, G_f(\chi^l)}{G_f^l(\chi^l)} \prod_{j=1}^{e} \prod_{k=1}^{r} \prod_{c=1}^{w^{r-k}} \frac{\bar{\chi}^{\delta l}(l)\, G_{fn}(\chi^{\delta l})}{1} \pmod{w},$$

so

$$\eta^l \equiv \frac{\chi^{l^2 - l - l\delta(l-1)/n}(l)\, G_{fn}^{(l-1)/n}(\chi^{\delta l})}{G_f^{l-1}(\chi^l)} \pmod{w}.$$

By (6), $G_{fn}(\chi^{\delta l}) = G_f^n(\chi^l)$; hence

$$\eta^l \equiv 1 \pmod{w}. \tag{11}$$

Thus w divides the norm $N(\eta^l - 1)$. By (10), η^l is an n-th root of unity. Thus if $\eta^l - 1 \neq 0$, then $N(\eta^l - 1)$ divides n, which contradicts the fact that $w \nmid n$. Therefore $\eta^l = 1 = \eta^n$, so since $(l, n) = 1$, $\eta = 1$.

5. Proof of (3)

Let η denote the right side of (3). We assume that $0 < \alpha < q - 1$. To see that this presents no loss of generality, we now show that η is unchanged when α is replaced by $\alpha + (q-1)j$, where j is an integer. Clearly $G_f(\chi^\alpha)$ and $\chi^\alpha(l)$ are unchanged, since the restriction $\chi|_{GF(q)}$ has order $q - 1$. Finally, $G_{fl}(\chi^{\alpha\beta})$ is also unchanged, as

$$G_{fl}(\chi^{\alpha\beta}) = G_{fl}(\chi^{\alpha\beta q^{\alpha_j}}) = G_{fl}(\chi^{\beta(\alpha + j(q-1))}), \tag{12}$$

where α_j is defined by $\alpha_j \alpha \equiv j \pmod{l}$, $\alpha_j \geqslant 0$.

Let $\psi = \chi^{\beta(q-1)}$. Using (6), we have

$$\eta^l = \frac{G_{fl}(\chi^{\alpha\beta l})}{\chi^{\alpha l}(l)\, G_{fl}^l(\chi^{\alpha\beta})} \prod_{j=1}^{l-1} G_{fl}(\psi^j).$$

For each $j \in \{0, 1, ..., l-1\}$, we have, by (12),

$$G_{fl}(\chi^{\alpha\beta}) = G_{fl}(\chi^{\alpha\beta}\psi^j).$$

Thus,

$$\eta^l = \frac{G_{fl}(\chi^{\alpha\beta l})}{\chi^{\alpha l}(l)} \prod_{j=0}^{l-1} \frac{G_{fl}(\psi^j)}{G_{fl}(\chi^{\alpha\beta}\psi^j)}. \tag{13}$$

Since $\chi^{\alpha l}(l) = \chi^{\alpha\beta l}(l)$, the right side of (13) equals 1 by (7), so

$$\eta^l = 1. \tag{14}$$

Let P be the prime ideal above p in $\mathcal{O} = Z[\omega]$, where

$$\omega = \exp(2\pi i/p(q^l - 1),$$

with P chosen such that χ is the character of order $q^l - 1$ on $\mathcal{O}/P \approx GF(q^l)$ which maps the coset $\omega + P$ to $\bar{\omega}$. To show that $\eta = 1$, it suffices to show that $\eta \equiv 1 \pmod{P}$. For, if $\eta \neq 1$, then by (14), the norm $N(\eta - 1)$ divides l; but if also $\eta \equiv 1 \pmod{P}$, then $p \mid N(\eta - 1)$, which yields the contradiction $p \mid l$.

For any integer x, let $L(x)$ denote the least nonnegative residue of $x \pmod{l}$. For integers $i \geqslant 0$, define

$$\varepsilon_i = \begin{cases} 1, & \text{if } 1 \leqslant L(i\alpha) \leqslant L(\alpha) \\ 0, & \text{otherwise}, \end{cases}$$

and

$$c_i = \varepsilon_i + l^{-1}(\alpha - L(\alpha) + (q-1)L(-i\alpha)).$$

Note that each c_i is an integer with $0 \leqslant c_i \leqslant q - 1$. We have

$$l\alpha\beta - l \sum_{i=1}^{l} c_i q^{i-1} = \sum_{i=1}^{l} q^{i-1}(\alpha - lc_i)$$

$$= \sum_{i=1}^{l} q^{i-1}\{-l\varepsilon_i + L(\alpha) - L((1-i)\alpha) + L(-i\alpha)\}.$$

The expressions in braces are easily seen to vanish. Thus we have the following explicit expansion of $\alpha\beta$ in base q:

$$\alpha\beta = \sum_{i=1}^{l} c_i q^{i-1}. \tag{15}$$

By (8), (14), and the definition of η,

$$\eta \equiv (u\gamma(\alpha))^{-1} l^\alpha \gamma(\alpha\beta) \pmod{P}, \tag{16}$$

where

$$u = \prod_{j=1}^{l-1} \gamma\big(j(q-1)/l\big).$$

By (15) and (16),

$$\eta \equiv \big(u\gamma(\alpha)\big)^{-1} l^{\alpha} \prod_{i=1}^{l} \gamma(c_i) \qquad (\text{mod } P).$$

Thus by the second congruence in (8), there is an integer M such that

$$u\eta \equiv \frac{1}{\alpha!} l^{\alpha} (\zeta-1)^M \prod_{i=1}^{l} c_i! \qquad (\text{mod } P). \tag{17}$$

First suppose that $0 < \alpha < l$. Then by (17) and the definition of c_i,

$$\begin{aligned} u\eta &\equiv \frac{1}{\alpha!} l^{\alpha} (\zeta-1)^M \prod_{i=1}^{l} \left(\frac{q-1}{l} L(-i\alpha)\right)! \prod_{j=1}^{\alpha} \left(1 + \frac{q-1}{l}(l-j)\right) \\ &\equiv (\zeta-1)^M \prod_{i=1}^{l} \left(\frac{q-1}{l} L(-i\alpha)\right)! \qquad (\text{mod } P). \end{aligned}$$

By (14), η is a unit, so again applying the second congruence in (8), we find that

$$u\eta \equiv \prod_{i=1}^{l} \gamma\left(\frac{q-1}{l} L(-i\alpha)\right) \qquad (\text{mod } P).$$

Since α is prime to l, the numbers $L(-i\alpha)$ run through a complete residue system (mod l) as i runs from 1 to l. Thus, be the definition of u following (16), we obtain the desired result $\eta \equiv 1$ (mod P) in the case $0 < \alpha < l$.

Finally, suppose that $l < \alpha < q-1$. We suppose as induction hypothesis that $\eta' \equiv 1$ (mod P), where η' is obtained from η by replacing α by $\alpha - l$. Then by (17) and the definition of c_i, there is an integer N such that

$$\begin{aligned} \eta \equiv \eta/\eta' &\equiv \frac{1}{\alpha!} (\zeta-1)^N (\alpha-l)!\, l^l \prod_{i=1}^{l} c_i \\ = \frac{1}{\alpha!} (\zeta-1)^N (\alpha-l)! &\prod_{i=1}^{l} \{l\varepsilon_i + \alpha - L(\alpha) + (q-1) L(-i\alpha)\} \qquad (\text{mod } P). \end{aligned}$$

Since the numbers $\{l\varepsilon_i - L(-i\alpha) + \alpha - L(\alpha)\}$ run through the l numbers $\alpha, \ldots, \alpha - l + 1$ as i runs from 1 to l, we see that $N = 0$ and $\eta \equiv 1$ (mod P).