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MINIMAL SPLITTING FIELDS FOR GROUP REPRESENTATIONS

BURTON I. FEIN

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Let T be a complex irreducible representation of a finite group G of order n and let χ be the character afforded by T. An algebraic number field $K \supset Q(\chi)$ is a splitting field for χ if T can be written in K. The minimum of $[K: Q(\chi)]$, taken over all splitting fields K of χ, is the Schur index $m_Q(\chi)$ of χ. In view of the famous theorem of R. Brauer that $Q(e^{2\pi i}/n)$ is a splitting field for χ, it is natural to ask whether there exists a splitting field L with $Q(e^{2\pi i}/n) \supset L \supset Q(\chi)$ and $[L: Q(\chi)] = m_Q(\chi)$. In this paper examples are constructed which show that such a splitting field L does not always exist. Sufficient conditions are also obtained which guarantee the existence of a splitting field L as above.

Throughout this paper Q will denote the field of rational numbers. If K is an algebraic number field and p is a prime of K, we denote the completion of K at p by K_p. If A is a simple component of a group algebra over Q, the center of A being K, and π_1 and π_2 are primes of K extending the rational prime p, then the indices of $A \otimes_K K_{\pi_1}$ and $A \otimes_K K_{\pi_2}$ are equal [2, Theorem 1]. We write $l.i._p A$ for this common value and refer to $l.i._p A$ as the p-local index of A. If $L \supset K$ and L is an abelian extension of Q, we refer to the ramification degree of a prime π of K from K to L as the q-ramification degree where π extends the rational prime q. Clearly, this does not depend on the choice of π. We use similar notation when referring to residue class degrees.

Throughout this paper χ will denote an irreducible complex character of a finite group G of order n. There is a unique constituent $\mathscr{A}$ of the group algebra of G over $Q(\chi)$ corresponding to χ in the sense that the representation of G afforded by a minimal left ideal of $\mathscr{A}$ is equivalent to $m_Q(\chi)T$, where T affords χ. If D is the division algebra component of $\mathscr{A}$ we say that D (and $\mathscr{A}$) is associated with χ. The index of D equals $m_Q(\chi)$ and χ is realizable in K if and only if K is a splitting field for D. We refer the reader to [1] for the relevant theory of algebras assumed.

We denote a primitive mth root of unity by ε_m. Gal (L/K) denotes the Galois group of L over K, and $[L: K]$ the degree of L over K. If A and B are two central simple K-algebras we write $A \sim B$ to denote that A and B are similar in the Brauer group of K.

A special case of the following lemma is proved in [6, page 631]:

LEMMA. *Let F be the completion of an algebraic number field at a finite prime and suppose the residue class field of F has q elements. Let p be a prime, $p \nmid q$, and suppose $p^t \mid q-1$, $p^{t+1} \nmid q-1$. Let E be a cyclic extension of F of degree $p^e \cdot p^f$ where p^e, $e > 0$, is the ramification degree of E over F. Let $\langle\sigma\rangle = \mathrm{Gal}(E/F)$ and let $\varepsilon_{p^s} \in F$.* We *have:*

(1) *Let $p^t = 2$ so $\varepsilon_{p^s} = -1$. Then the cyclic algebra $(E, \sigma, -1)$ has index 2.*

(2) *Suppose $p^t \geqq 3$ and $s \geqq v > 0$. Then $(E, \sigma, \varepsilon_{p^s})$ has index p^v if and only if $t = e + s - v$.*

Proof. By Hensel's lemma, $\varepsilon_{p^t} \in F$, $\varepsilon_{p^{t+1}} \notin F$. Let $[K: F] = p^f$, K unramified over F. All p-power roots of unity in E are in K. If $p^t \geqq 3$, an easy induction shows that E contains a primitive p^{t+f}th root of unity but does not contain a primitive p^{t+f+1}th root of unity. If $p^t = 2$ and $f > 0$, then E contains a primitive 2^{2+f}th root of unity but not a primitive 2^{3+f}th root of unity. If $p^t = 2$ and $f = 0$, then E does not contain ε_4. From the theory of cyclic algebras over local fields, $(E, \sigma, \varepsilon_{p^s})$ has index p^v if and only if $\varepsilon_{p^{s-v}}$ is a norm from E to F but $\varepsilon_{p^{s-v+1}}$ is not a norm. Suppose $\varepsilon_{p^{s-v}}$ is a norm from E to F. Let N denote the norm map from E to F. Since $\varepsilon_{p^{s-v}}$ is a unit, $\varepsilon_{p^{s-v}} = N(\gamma)$ where γ is a unit of E. Let U_E, U_{E^1} denote, respectively, the units and the units (mod 1) of E. We have $U_{E/U_E^1} \cong \bar{E}^*$, the multiplicative group of the residue claas field of E. Since E and K have the same residue class field, there is a root of unity δ in K with $\gamma U_{E^1} = \delta U_{E^1}$. Since $N(\delta) U_{F^1} = \varepsilon_{p^{s-v}} U_{F^1} = N(\delta) U_{F^1}$, we may assume that δ has p-power order. Let N' denote the norm from K to F. Then $N(\delta) = N'(\delta^{p^e})$ since $\delta \in K$. Since Gal (K/F) is generated by the Frobenius automorphism, we have $N(\delta) = \delta^{mp^e}$ where

$$m = (q^{p^f} - 1) / (q - 1) .$$

Suppose (1) holds so $p^t = 2$, $\varepsilon_{p^s} = -1$. $(E, \sigma, -1)$ has index 1 or 2 and we have index 1 if and only if -1 is a norm from E. By the argument above, if -1 is a norm, then $-1 U_{F^1} = \delta^{m2^e} U_{F^1}$ where δ is a 2-power root of unity, $e > 0$, and $m = (q^{2^f} - 1)/(q - 1)$. One verifies easily that $\delta^{m2^e} = 1$, a contradiction.

Now suppose (2) holds. Assuming $\varepsilon_{p^{s-v}}$ is a norm from E we obtain, as above, that $N(\delta)$ is a power of a primitive p^{t-e}th root of unity. Thus $t - e \geqq s - v$ so $t \geqq s + e - v$. Conversely, if $t = s + e - v$, then E contains a primitive $p^{s+e+f-v}$th root of unity ζ. An easy calculation using the Frobenius automorphism shows that $N(\zeta^u) = \varepsilon_{p^{s-v}}$ for some u. Let $\mathscr{A} = (E, \sigma, \varepsilon_{p^s})$ so $\mathscr{A}^{p^v} \sim (E, \sigma, \varepsilon_{p^{s-v}})$. If $t = s + e - v$, then we have shown that $\mathscr{A}^{p^v} \sim F$. If $\mathscr{A}^{p^{v-1}} \sim F$, then we would have $t \geqq s + e - v + 1$ which is not the case. Thus $t = s + e - v$ implies $\mathscr{A}$ has index p^v. Conversely, if $\mathscr{A}$ has index p^v, then $t \geqq s + e - v$. If $t \geqq s + e - v + 1$ we would have $\mathscr{A}^{p^{v-1}} \sim F$. Thus $t = s + e - v$, proving the lemma.

We can now construct an example (actually one for each prime p) of an irreducible character χ of a finite group G of order n such that $m_Q(\chi) = p$ but no subfield L of $Q(\varepsilon_n)$ with $[L: Q(\chi)] = p$ is a splitting field for χ.

EXAMPLE. Let p be an arbitrary prime. Let r be prime, $r \equiv 1 \pmod{p^2}$, $r \not\equiv 1 \pmod{p^3}$. Let q be a prime, $q \equiv 1 \pmod{r}$, $q \equiv 1 \pmod{p^4}$, and $q \not\equiv 1 \pmod{p^5}$. Let F be the subfield of $Q(\varepsilon_q)$ with $[Q(\varepsilon_q): F] = p^4$ and let E be the subfield of $Q(\varepsilon_r)$ with $[Q(\varepsilon_r): E] = p^2$. Let $\langle\sigma\rangle = \mathrm{Gal}\,(Q(\varepsilon_{p^3qr})/F(\varepsilon_{p^3r}))$ and $\langle\tau\rangle = \mathrm{Gal}\,(Q(\varepsilon_{p^3qr})/E(\varepsilon_{p^3q}))$. Let K be the fixed field of $\langle\sigma\tau\rangle$. Then $K(\varepsilon_q) = Q(\varepsilon_{p^3qr})$ and $[K(\varepsilon_q): K] = p^4$. Since q is totally ramified from $EF(\varepsilon_{p^3})$ to $F(\varepsilon_{p^3q})$ and splits completely from $EF(\varepsilon_{p^3})$ to $E(\varepsilon_{p^3r})$, we see that q is totally ramified from $EF(\varepsilon_{p^3})$ to K. Thus the ramification degree of q from K to $K(\varepsilon_q)$ is p^2 and the residue class degree is 1.

Let $G = \langle w, x, y, z \mid w^q = x^r = z^{p^3} = 1, y^{p^4} = z, z \text{ central}, (w, x) = 1, y^{-1}wy = w^a, y^{-1}xy = x^b\rangle$ where $\sigma\tau(\varepsilon_q) = (\varepsilon_q)^a$ and $\sigma\tau(\varepsilon_r) = (\varepsilon_r)^b$. The cyclic algebra $\mathscr{A} = (Q(\varepsilon_{p^3qr}), \sigma\tau, \varepsilon_{p^3})$ is a homomorphic image of the group algebra of G over Q and so there exists a complex irreducible representation T of G with character χ such that the enveloping algebra of T is $\mathscr{A}$ and $Q(\chi) = K$. The index of $\mathscr{A}$ equals $m_Q(\chi)$.

By the lemma we see that $\mathscr{A}$ has q-local index p. Since $K(\varepsilon_q) = Q(\varepsilon_{p^3qr})$, r is unramified from K to $Q(\varepsilon_{p^3qr})$ and so the r-local index of $\mathscr{A}$ is 1. Since the 2-local index is at most 2 [7, Satz 11] and at infinite primes $\mathscr{A}$ can only have index 1 or 2, we conclude that $m_Q(\chi) = p$. $|G| = p^7qr$ and $\mathrm{Gal}\,(Q(\varepsilon_{p^7qr})/K) \cong C_{p^4} \times C_{p^4}$. Since $q \equiv 1 \pmod{p^4}$ we see that q splits completely in the unique extension J of K, $J \subset Q(\varepsilon_{p^7qr})$, $\mathrm{Gal}\,(J/K) = C_p \times C_p$. It follows, therefore, that q splits completely in every subfield of $Q(\varepsilon_{p^7qr})$ of degree p over K and so T is not realizable in any subfield L of the $|G|$th roots of unity with $[L: Q(\chi)] = p$.

We next prove that under certain conditions there always exists a subfield L of the order of $|G|$th roots of unity which is a splitting field for χ and where $[L: Q(\chi)] = m_Q(\chi)$.

THEOREM. *Let χ be a complex irreducible character of a finite group G of exponent n with $m_Q(\chi) \geqq 3$. Assume either* (a) *or* (b) *below hold:*

(a) *$Q(\chi) = Q(\varepsilon_m)$ for some m.*

(b) *$n = p^a q^b$ where p and q are primes, $p < q$.*

Then there exists a subfield L of $Q(\varepsilon_n)$ with $[L: Q(\chi)] = m_Q(\chi)$ and such that L is a splitting field for χ.

Proof. By a standard reduction using the Brauer-Witt theorem [8, § 2], we may assume that $m_Q(\chi)$ is a prime power. Since if (b) holds, $m_Q(\chi)$ is a power of p by [7, Satz 10], we will assume that $m_Q(\chi) = p^c$.

Let K be the subfield of $Q(\varepsilon_n)$ such that $K \supset Q(\chi)$, $p \nmid [K: Q(\chi)]$, and $[Q(\varepsilon_n): K]$ is a power of p. Let D be the $Q(\chi)$-central division algebra associated with χ. By the Brauer-Witt theorem [8, § 2], $D \otimes_{Q(\chi)} K$ is similar to a crossed product $(K(\psi)/K, \beta)$ where ψ is a linear character of a subgroup of G, β is a factor set whose values are roots of unity, and where $\mathrm{Gal}\,(K(\psi)/K)$ is isomorphic to a factor group of a Sylow p-subgroup of G.

$Q(\chi)$ contains a primitive $m_Q(\chi)$th root of unity [3, Theorem 1]. Since $m_Q(\chi) \geqq 3$, $Q(\chi)$ and K are both totally imaginary. Thus the nonzero invariants of D are at finite primes.

Suppose (a) holds, so $Q(\chi) = Q(\varepsilon_m)$. We may assume m is not twice an odd number. We have $m_Q(\chi) \mid m$. If r is a prime divisor of m, $r \neq p$, then since, for some d, $[Q(\varepsilon_n): K] = p^d$, r is unramified from K to $K(\psi)$. This implies that the r-local index of D equals 1. Now let $q_1, \cdots, q_t$ be the rational primes at which D has nontrivial local index. Let the q_i-local index of D be p^{c_i}. Then $c_i \leqq c$ for all i and $c_i = c$ for some i since D has index p^c. Suppose q_i is odd. By [7, Satz 10] $p^{c_i} \mid q_i - 1$ and so $Q(\varepsilon_{q_i})$ has a subfield E_i with $[E_i: Q] = p^{c_i}$. Since $q_i \nmid m$, $[E_iQ(\chi): Q(\chi)] = p^{c_i}$ and q_i is totally ramified from $Q(\chi)$ to $E_iQ(\chi)$. Let $L_i = E_iQ(\chi)$. By [3, Theorem 1], $\varepsilon_{p^{c_i}} \in Q(\chi)$ and so $L_i = Q(\chi)(\alpha_i)$ where $\alpha_i^{p^{c_i}} \in Q(\chi)$. If all of the q_i are odd, let $\alpha = \alpha_1\alpha_2 \cdots \alpha_t$. If $q_1 = 2$, say, let $a = \sqrt{-1}\alpha_2 \cdots \alpha_t$. We note that q_1 can equal 2 only if $p^{c_1} = 2$ and $\sqrt{-1} \notin Q(\chi)$ [7, Satz 11]. If this happens, then $4 \mid n$ by [4]. Thus $\alpha \in Q(\varepsilon_n)$. Since $\alpha^{p^c} \in Q(\chi)$, $[Q(\chi)(\alpha): Q(\chi)] \leqq p^c$. Since q_i is ramified of degree p^{c_i} from $Q(\chi)$ to $Q(\chi)(\alpha)$, $[Q(\chi)(\alpha): Q(\chi)] = p^c$ and $Q(\chi)(\alpha)$ splits D. Thus $Q(\chi)(\alpha)$ is our desired field.

Assume (b) holds. $K(\psi)$ is an abelian extension of K generated by roots of unity. Since $(K(\psi)/K, \beta)$ has index $p^c > 1$, $(K(\psi)/K, \beta)$ has q-local index p^c and so q is ramified from K to $K(\psi)$. This implies that $K(\psi) \supset K(\varepsilon_q) = K(\varepsilon_{q^b})$. Since $m_Q(\chi) = p^c \geqq 3$, if $p = 2$ we see that $\sqrt{-1} \in K$. In view of [7, Satz 12] this implies that q is the only prime of Q with the q-local index of $(K(\psi)/K, \beta)$ different from 1.

Let $\varepsilon_{p^v} \in K(\psi)$, $\varepsilon_{p^{v+1}} \notin K(\psi)$. We note that $K(\psi) = Q(\varepsilon_{p^v q^b})$ since $[Q(\varepsilon_{p^a q^b}): K]$ is a power of p. Let $\langle\sigma\rangle = \mathrm{Gal}\,(Q(\varepsilon_{p^v q^b})/Q(\varepsilon_{p^v}))$, $\langle\tau\rangle = \mathrm{Gal}\,(Q(\varepsilon_{p^v q^b})/Q(\varepsilon_{q^b}))$. Then $\langle\sigma^i\tau^j\rangle = \mathrm{Gal}\,(Q(\varepsilon_{p^v q^b})/K)$ for some i and j. Let F_1 and F_2 be, respectively, the fixed fields of $\langle\sigma^i\rangle$ and $\langle\tau^j\rangle$. Let

p^e and p^t be, respectively, the order, of $\langle\sigma^i\rangle$ and $\langle\tau^j\rangle$. Let L_1 and L_2 be, respectively, the subfields of index p^e and p^t in $Q(\varepsilon_{q^b})$ and $Q(\varepsilon_{p^v})$. Then $F_1 = L_1(\varepsilon_{p^v})$ and $F_2 = L_2(\varepsilon_{q^b})$ and $F_1 \cap F_2 = L_1L_2$. Since q is totally ramified from L_1L_2 to F_2 and is unramified from L_1L_2 to F_1, q is totally ramified from L_1L_2 to K. Thus $e > t$ and q has ramification degree p^{e-t} from K to $K(\psi)$.

Suppose $[K(\varepsilon_{p^v}): K] = p^s$. Then $(\sigma^i\tau^j)^{p^s}$ fixes $K(\varepsilon_{p^v})$. Since σ fixes ε_{p^v}, τ^{jp^s} fixes ε_{p^v} and so $\tau^{jp^s} = 1$. Thus $s \geqq t$. But q is unramified from K to $K(\varepsilon_{p^v})$ and so the ramification degree of q from K to $K(\psi)$ is at most p^{e-s}. Thus $e - s \geqq e - t$ so $s = t$. This shows that q is totally ramified from $K(\varepsilon_{p^v})$ to $K(\psi)$. Since q is unramified from $K(\psi)$ to $K(\varepsilon_{p^aq^b}) = Q(\varepsilon_{p^aq^b})$, we see that $K(\varepsilon_{p^a})$ is the maximal extension of K inside $Q(\varepsilon_{p^aq^b})$ in which q is unramified.

$Q(\varepsilon_{p^aq^b})$ is not a cyclic extension of K by [5]. Thus Gal $(Q(\varepsilon_{p^aq^b})/K)$ is the direct product of two cyclic groups. Let M_1 and M_2 be subfields of $Q(\varepsilon_{p^aq^b})$ such that $M_1 \cap M_2 = K$, $Q(\varepsilon_{p^aq^b}) = M_1M_2$, and M_1 and M_2 are cyclic extensions of K. Since $K(\varepsilon_{p^a})$ is cyclic over K, q must be totally ramified in either M_1 or M_2. Suppose q is totally ramified in M_1. By [5], since $Q(\varepsilon_{p^aq^b})$ is cyclic over M_1, M_1 is a splitting field for χ. Thus M_1 splits $(K(\psi)/K, \beta)$ and so $[M_1: K] \geqq p^c$. The subfield L of M_1 with $[L: Q(\chi)] = p^c$ is the desired splitting field for χ. This completes the proof of the theorem.

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