

## §3. Remarks

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$$(11) \quad \rho_m \leq d + (m + 1)(d - 1).$$

Also, from (5), (10) and (11) we get (recalling our definition of  $\deg 0$ ),

$$(12) \quad \begin{cases} \sigma_0 = (r + 1)d - p \\ \sigma_{m+1} \leq \max(\sigma_m + d, \rho_m) - p \leq \max(\sigma_m, (m + 1)(d - 1)) + d - p. \end{cases}$$

Observe that we have  $\sigma_0 = (r + 1)d - p = (r + 1)d - (2r + 1) = (d - 2)r + (d - 1) \geq d - 1$ . Suppose that the inequality

$$(13) \quad \sigma_m \geq (m + 1)(d - 1)$$

is true for  $m = 0, \dots, M - 1$ , but not for  $m = M$  (possibly  $M = \infty$ ). Then  $M \geq 1$ . Moreover, by (12) we have  $\sigma_{m+1} \leq \sigma_m + d - p$  for  $m \leq M - 1$ , whence

$$(14) \quad \sigma_m \leq \sigma_0 + m(d - p) = rd - (m + 1)(p - d), \quad \text{for } m \leq M.$$

Applying (13) and (14) with any  $m \leq M - 1$ , we get  $rd - (m + 1)(p - d) \geq (m + 1)(d - 1)$ , i.e.  $2r(m + 1) \leq rd$ . Therefore we have

$$(15) \quad M \leq \frac{d}{2}.$$

Finally, apply (12) for  $m = M$  and observe that  $M \leq d/2 \leq r - 1$ , hence  $S_{M+1} \neq 0$  by the Claim. We obtain  $0 \leq \sigma_{M+1} \leq (M + 1)(d - 1) + d - p$ , whence, comparing with (15),

$$2p \leq \begin{cases} d^2 + 3d - 2 & \text{if } d \text{ is even} \\ d^2 + 2d - 1 & \text{if } d \text{ is odd.} \end{cases}$$

This proves the theorem and more.  $\square$

### §3. REMARKS

(1) The method gives some information also in the case of a general finite field  $\mathbf{F}_q$ . The same arguments as above work everywhere, on replacing  $p$  by  $q$ , except that in the Claim we must now suppose that  $m \leq r_0$ , where  $p = 2r_0 + 1$ . The final conclusion will be that  $d \geq \min(r_0, \sqrt{2q} - (3/2))$ . This is still sufficient to prove that equations  $y^2 = f(x)$  in  $\mathbf{F}_q$  have some solution, provided  $p$  is sufficiently large compared to  $\deg f$ .

(2) The same method of proof produces a lower bound for the number  $N'$  of solutions of  $y^2 = f(x)$  such that  $y \neq 0$ . This bound is better than the one which has been stated above, as a corollary of the theorem itself. To

derive this bound we define  $S := \{u \in \mathbf{F}_p : f(u) \text{ is not a square in } \mathbf{F}_p\}$  and put  $g(X) := \prod_{u \in S} (X - u)$ . Then we observe that

$$g(X)f(X)^{r+1} - g(X)f(X) = (X^p - X)S(X).$$

This equation generalizes (5) above. At this point we follow completely the above proof of the theorem. The differential operators will now be defined by

$$\begin{aligned} \Delta_m(\phi)(X) &:= g(X)f(X)\phi'(X) \\ &\quad - ((r + m + 1)g(X)f'(X) + (m + 1)g'(X)f(X))\phi(X). \end{aligned}$$

The conclusion will be that

$$2 \deg g \geq \frac{4(p - 1)}{d + 4} - 2(d - 1).$$

Apply this result with  $af(X)$  in place of  $f(X)$ , where  $a$  is a quadratic nonresidue in  $\mathbf{F}_p$ . Then observe that the left side is just  $N'$ .

(3) As announced in §1, we give a simple proof of the upper bound  $d(p) \leq 2m(p)$  (defined in the introduction). Define  $N_c$  as the number of monic polynomials in  $\mathbf{F}_p[X]$  which are irreducible and have degree  $c$ . By counting elements in the field  $\mathbf{F}_{p^c}$  we easily find the following formula (which goes back to Gauss), i.e.

$$\sum_{r|c} rN_r = p^c,$$

the sum running over positive divisors of  $c$ . For  $c \geq 3$  this easily implies

$$\sum_{2 \leq d \leq c} N_d \geq \frac{p^c}{c}.$$

Let  $g(X) \in \mathbf{F}_p[X]$  be monic, irreducible of degree  $d \geq 2$  and consider the vector whose entries are the Legendre symbols  $\left(\frac{g(u)}{p}\right)$ , for  $u \in \mathbf{F}_p$ . Since each entry lies in  $\{\pm 1\}$ , the number of possibilities for the vector is  $\leq 2^p$ . If we let  $g$  run through all such polynomials, with  $2 \leq d \leq c$ , the number of possibilities for  $g$  will be  $\geq p^c/c$ . For  $c = m(p)$ , this quantity exceeds  $2^p$  by definition. Hence there will be distinct choices  $g_1(X), g_2(X)$  for  $g(X)$ , giving rise to the same vector. This means that the polynomial  $f(X) := g_1(X)g_2(X)$  assumes nonzero square values on the whole of  $\mathbf{F}_p$ . Moreover, since  $g_1, g_2$  are distinct, monic and irreducible,  $f(X)$  has no square factor of positive degree. Therefore we have  $d(p) \leq \deg f \leq 2m(p)$ , as stated.