Proof of the prime power conjecture for projective planes of order n with abelian collineation groups of order n^2

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Abstract

Let G be an abelian collineation group of order n^2 of a projective plane of order n. We show that n must be a prime power and that the p-rank of G is at least $b+1$ if $n = p^b$ for an odd prime p.

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1 Introduction

The purpose of this note is a surprisingly elementary proof of the following result.

Theorem 1.1 *Let G be an abelian collineation group of order n^2 of a projective plane of order n. Then n is a prime power, say $n = p^b$. If $p > 2$, then the p-rank of G is at least $b + 1$.*

Theorem 1.1 is the most conclusive known result in the context of the prime power conjecture for projective planes. Let us consider some background. Among other things, Dembowski and Piper [3] showed that there are only three possible types of projective planes of order n with abelian collineation groups G of order n^2. These are translation planes, dual translation planes and the so-called type (b) planes. By a classical result of André [1], in the case of translation planes and dual translation planes, the collineation group G is always an elementary abelian p-group. Following [3], a projective plane of order n is called a *type* (b) *plane* if it has an abelian collineation group of order n^2 whose orbits on the point set $\mathcal{P}$ are $\{p\}$, $L \setminus \{p\}$ and $\mathcal{P} \setminus L$ where (p, L) is a suitable incident point-line pair. In this case, we call G a *group of type* (b). Such groups exist for all prime powers n, see [2] or [7]. As a consequence of the prime power conjecture for projective planes, it has been conjectured that groups of type (b) only exist for prime powers n. Combining the results of André and Dembowski and Piper, we have the following.

Result 1.2 [1, 3] *Let Π be a projective plane of order n with an abelian collineation group G of order n^2. Then one of the following hold.*
(a) Π is a translation plane or its dual, n is a prime power and G is elementary abelian.
(b) Π is a plane of type (b).

Groups of type (b) are closely related to planar functions. Let H and K be groups of order n. A *planar function* of degree n is a map $f : H \to K$ such that for every $h \in H \setminus \{1\}$ the induced map $f_h : x \mapsto f(hx)f(x)^{-1}$ is bijective. If a planar function from H to K exists, then $H \times K$ is a group of type (b), see [2, 7]. Thus Theorem 1.1 implies the following.

Corollary 1.3 *If there is a planar function of degree n between abelian groups, then n is a prime power.*

The prime power conjecture for planar functions has been studied in many papers. The best result previous to Corollary 1.3 is due to S.L. Ma [6].

2 The result

A good way to talk about collineation groups of type (b) is to use the group ring. We first introduce the necessary notation. Let G be a multiplicatively written finite group with identity element 1. For $X = \sum a_g g \in \mathbb{Z}[G]$ we write $|X| = \sum a_g$, $X^{(t)} = \sum a_g g^t$ and $[X]_1 = a_1$ (the coefficient of 1 in X). For $r \in \mathbb{Z}$ we write r for the group ring element $r \cdot 1$, and for $S \subset G$ we write S instead of $\sum_{g \in S} g$. It is well known [5] that an abelian group G of order n^2 is a group of type (b) on a suitable projective plane of order n if and only if there is a subgroup N of order n of G and an n-subset D of G such that

$$DD^{(-1)} = n + G - N \tag{1}$$

in $\mathbb{Z}[G]$. The set D in is called an $(n, n, n, 1)$ *difference set* in G relative to N.
We prepare the proof of our main result with two lemmas. Let G be a finite abelian group, and let p be a prime. By $r_p(G)$ we denote the p-rank of G, i.e. the minimum number of generators of the Sylow p-subgroup of G.

Lemma 2.1 *Let G be a finite abelian group, let N be a subgroup of G, and let p be a prime. Then*

$$\begin{aligned} [G^{(p)}]_1 &= p^{r_p(G)} \\ [G^{(p)}N]_1 &= p^{r_p(G/N)}|N|. \end{aligned}$$

Proof Straightforward checking. □

Lemma 2.2 *Let G be an abelian group, let $D \in \mathbb{Z}[G]$ with $|D| = k$ and*

$$\begin{aligned} DD^{(-1)} &= k + X, \\ DX &= aG \end{aligned}$$

for some integer a and $X \in \mathbb{Z}[G]$. Furthermore, let $p \geq 3$ be a prime dividing k. Then

$$(p-1)k^2 \leq k[X + X^{(p)}]_1 + [XX^{(p)}]_1$$

with equality if and only if $D^{(-1)}D^{(p)}$ has coefficients 0 and p only.

Proof Write $A := D^{(-1)}D^{(p)} = \sum a_g g$. Then $\sum a_g = k^2$. Since G is abelian, we have $D^{(p)} = D^p$ in $\mathbb{Z}_p[G]$. As k is divisible by p, we get

$$A = (k + X)D^{p-1} = XD^{p-1} = aGD^{p-2} = akGD^{p-3} = 0$$

in $\mathbb{Z}_p[G]$. Hence all a_g are divisible by p and thus

$$\sum a_g^2 \geq p \sum a_g = pk^2$$

with equality if and only if $a_g \in \{0, p\}$ for all g. On the other hand, we have

$$AA^{(-1)} = (k + X)(k + X^{(p)}) = k^2 + k(X + X^{(p)}) + XX^{(p)}$$

and thus

$$\sum a_g^2 = [AA^{(-1)}]_1 = k^2 + k[X + X^{(p)}]_1 + [XX^{(p)}]_1.$$

This proves the lemma. □

Now we are ready to prove our main result.

Theorem 2.3 *Let D be the relative difference set satisfying* (1), *and let $p \geq 3$ be a prime divisor of n. Then*

$$(p-2)n \leq p^{r_p(G)} - p^{r_p(N)} - p^{r_p(G/N)}.$$

Proof Since $|D| = n$, (1) implies that D contains exactly one element of each coset of N in G, i.e.

$$DN = G. \tag{2}$$

Because of (1) and (2), we can apply Lemma 2.2 with $X = G - N$ and $k = n$. Note that $[X + X^{(p)}]_1 = p^{r_p(G)} - p^{r_p(N)}$ using Lemma 2.1. Furthermore,

$$[XX^{(p)}]_1 = [(n^2 - n)G - G^{(p)}N + nN]_1 = n^2 - np^{r_p(G/N)}$$

again using Lemma 2.1. Thus Lemma 2.2 gives us

$$(p-1)n^2 \leq n(p^{r_p(G)} - p^{r_p(N)}) + n^2 - np^{r_p(G/N)}.$$

Subtracting n^2 and dividing by n gives the assertion. □

Proof of Theorem 1.1
In view of Result 1.2, we can assume that G is a group of type (b). It is shown in [4] that n must be a power of 2 if n is even. Thus we can assume that n is odd. If n is not a prime power, then there is a prime divisor $p \geq 3$ of n such that the Sylow p-subgroup S of G has order less than n. But then $p^{r_p(G)} \leq |S| < n$ contradicting Theorem 2.3. Thus n is a prime power, say $n = p^b$ where p is an odd prime. Theorem 2.3 shows $p^{r_p(G)} > n$, and so G must have rank at least $b + 1$. □

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