Hardy Ramanujan Journal
Vol. 28(2005) 30-34

A lower bound concerning subset sums which do not cover all the residues modulo p

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ABSTRACT

Let $c > \sqrt{2}$ and let p be a prime number. J-M. Deshouillers and G. A. Freiman proved that a subset $\mathcal{A}$ of $\mathbb{Z}/p\mathbb{Z}$, with cardinality larger than $c\sqrt{p}$ and such that its subset sums do not cover $\mathbb{Z}/p\mathbb{Z}$ has an isomorphic image which is rather concentrated; more precisely, there exists s prime to p such that

$$\sum_{a\in\mathcal{A}} \|\frac{as}{p}\| < 1 + O(p^{-1/4}\ln p),$$

where the constant implied in the "O" symbol depends on c at most. We show here that there exist a constant K depending on c at most, and such sets $\mathcal{A}$, such that for all s prime to p one has

$$\sum_{a\in\mathcal{A}} \|\frac{as}{p}\| > 1 + Kp^{-1/2}.$$

1 Let p be a prime number and $\mathcal{A}$ be a set of distinct non-zero residue classes modulo p. We denote by $\mathcal{A}^*$ the set of the subset sums of $\mathcal{A}$, that is to say

$$\mathcal{A}^* = \{\sum_{b\in\mathcal{B}} b,\ \mathcal{B} \subset \mathcal{A}\}.$$

G. A. Freiman and the author proved (cf. [1]) the following result.

[1]Supported by Université Victor Segalen Bordeaux 2 (EA 2961), Université Bordeaux1 and CNRS (UMR 5465)

Theorem 1. *Let $c > \sqrt{2}$. Let p be a prime number and $\mathcal{A}$ be a subset of $\mathbb{Z}/p\mathbb{Z}$ with cardinality larger than $c\sqrt{p}$, such that its subset sums do not cover $\mathbb{Z}/p\mathbb{Z}$. There exists s prime to p such that*

$$\sum_{a\in\mathcal{A}} \|\frac{as}{p}\| < 1 + O(p^{-1/4}\ln p). \tag{1}$$

In this paper we prove that the error term cannot be arbitrary small. More precisely, we prove the following

Theorem 2. *Let $\sqrt{2} < c < 2$. There exists a positive real number K such that for all prime number p which is sufficiently large, there exists a subset $\mathcal{A}$ of $\mathbb{Z}/p\mathbb{Z}$ with cardinality larger than $c\sqrt{p}$, such that its subset sums do not cover $\mathbb{Z}/p\mathbb{Z}$, and such that for every s prime to p, one has*

$$\sum_{a\in\mathcal{A}} \|\frac{as}{p}\| > 1 + Kp^{-1/2}. \tag{2}$$

2 Notation

When a and b are two real numbers, we denote by $\langle a, b\rangle$ the set of the integers x from the interval $[a, b]$. For a real number u, we use the traditional notation $e(u) = \exp(2\pi i u)$ and $\|u\| = \min_{z\in\mathbb{Z}} |u - z|$; when $b \in \mathbb{Z}/p\mathbb{Z}$, the expression $e(b/p)$ (*resp.* $\|b/p\|$) denotes the common value of all the $e(\tilde{b}/p)$'s (*resp.* $\|\tilde{b}/p\|$), where $\tilde{b}$ is any integer representing the class b ; we further let $|b|$ denote the minimum of $|\tilde{b}|$ over all the representative $\tilde{b}$ of b, or equivalently $|b| = p\|b/p\|$.

The letter p denotes a prime number which is sufficiently large to satisfy all the implicit or explicit inequalities.

3 A lemma

Before embarking on the construction of $\mathcal{A}$, we state and prove a preliminary technical lemma.

Lemma 1. *Let u and k be natural integers with $2 \le u \le 2k - 3$. Then any integer v in the interval $[k+2, 2k^2 - 3k]$ can be expressed as a sum of at most v/k pairwise distinct elements from the interval $[k+2, 5k]$.*

Proof of Lemma 1 The lemma is trivial when $k + 2 \le v \le 5k$ and we may now assume that $v > 5k$. Let us write $v = 2qk + r$ with $1 \le q \le 2k - 4$ and $3k < r \le 5k$, and let us consider two cases

- if q is even, say $q = 2\ell$, we have $\ell \le k-2$ and we can write $2qk = \sum_{|h|\le \ell, h\neq 0}(2k+h)$,

- if q is odd, say $q = 2\ell+1$, we have $\ell \le k-2$ and we can write $2qk = \sum_{|h|\le \ell}(2k+h)$.

In each case, we can represent v as a sum of $q+1$ pairwise distinct integers from the interval $[k+2, 5k]$, whence the result.

4 Construction of $\mathcal{A}$

4.1 We first construct an auxiliary suitable set of integers, $\mathcal{E}$. We recall that $\sqrt{2} < c < 2$ and let

$$L = \max\{12, \lfloor \frac{4+c^2}{4-c^2} + 1 \rfloor\} \text{ and } k = \lfloor \sqrt{\frac{p}{L^2-1}} + 1 \rfloor;$$

we thus have

$$(L^2-1)(k^2-4k+4) \le p \le (L^2-1)(k^2-2k+1).$$

We consider the set $\mathcal{B} = \langle k+1, Lk \rangle$; we have

$$2\sum_{b\in\mathcal{B}} b = (L^2-1)k^2 + (L-1)k,$$

from which one deduces

$$(0.5L-1)k - 0.5 \le \sum_{b\in\mathcal{B}} b - (k+1) - (p-1)/2 \le (L^2+0.5L)k.$$

By Lemma 1, when p is sufficiently large, we can find distinct elements in $\langle k+2, 5k \rangle$ the sum of which is $\sum_{b\in\mathcal{B}} b - (k+1) - (p-1)/2$; let us denote by $\mathcal{C}$ the set of those elements and let $\mathcal{D} = \mathcal{B}\backslash\mathcal{C}$. The set $\mathcal{D}$ is included in $\langle k+1, Lk \rangle$, contains $\{k+1\} \cup \langle 5k+1, Lk \rangle$ and satisfies

$$S := \sum_{d\in\mathcal{D}} d = (p-1)/2 + (k+1).$$

We finally define $\mathcal{E}$ by

$$\mathcal{E} = \mathcal{D} \cup \{-d / d \in \mathcal{D} \text{ and } d > k+1\}.$$

4.2 Let us now turn our attention to the set $\mathcal{E}^*$ in $\mathbb{Z}$. Its largest positive element is S (defined as $\sum_{d\in\mathcal{D}} d = (p-1)/2 + (k+1)$), the sum of the positive elements of $\mathcal{E}$. We have *a priori* two ways to get the largest element in $\mathcal{E}^*$ besides the one we just mentioned: either we subtract the smallest positive element of $\mathcal{E}$ (which is $k+1$), or we add its negative element with the minimal absolute value (which is at most $-(k+2)$); there are thus no element of $\mathcal{E}^*$ between $S-(k+1)$, which is $(p-1)/2$ and S, which is strictly larger than $(p+3)/2$. On the other hand, by a similar computation, the smallest element in $\mathcal{E}^*$ is the sum of the negative elements of $\mathcal{E}$, which is $-(S-(k+1)) = -(p-1)/2$, and the smallest besides it, is larger than or equal to $-(S-(k+1)-(k+2)) = -(p-1)/2+(k+2)$.

4.3 Let $\mathcal{A}$ be the canonical image of $\mathcal{E}$ on $\mathbb{Z}/p\mathbb{Z}$. We show that $\mathcal{A}^*$ does not cover $\mathbb{Z}/p\mathbb{Z}$: let us consider the point $(p+3)/2$ (or more correctly, its canonical image in $\mathbb{Z}/p\mathbb{Z}$). The only integers in $\mathcal{E}^*$ that can cover this point are $(p+3)/2$, which impossible, or $(p+3)/2-p = -(p-3)/2 = -(p-1)/2+1$, which is again impossible. Thus $\mathcal{A}$ is different from $\mathbb{Z}/p\mathbb{Z}$.

5 No dilation of $\mathcal{A}$ leads to a small sum It remains to show that relation (2) is satisfied.

5.1 We first consider the case when s is 1 or -1. In this case, we have $\sum_{a\in\mathcal{A}} \|sa/p\| = 2(S/p) - (k+1)/p = 1 + k/p > 1 + ((1/\sqrt{(L^2-1)}).p^{-1/2})$.

5.2 When $1 < |s| < p/(2Lk)$, we have $\|sa/p\| = |s|.\|a/p\|$ and so $\sum_{a\in\mathcal{A}} \|sa/p\| > |s|.(1+k/p) > 2$.

5.3 Let us now consider the case when $p/(2Lk) \leq |s| \leq p/((L-6)k)$. The interval $\langle 5k+1, 6k\rangle$ is in $\mathcal{D}$ and for any integer d in this interval we have $2/L < |s|d/p < p/2$; this implies $\sum_{a\in\mathcal{A}} \|sa/p\| > 2k/L$, which is larger than 2 when p is large enough.

5.4 We finally consider the case when $p/((L-6)k) \leq |s| < p/2$. For any real number x we have $2\pi\|x\| \geq 2|\sin(\pi x)| \geq 2\sin^2(\pi x) = 1-\cos(2\pi x) = 1 - \Re(e(x))$. Since the interval $\langle 5k+1, Lk\rangle$ is included in $\mathcal{D}$, we have

$$\sum_{a\in\mathcal{A}} \|sa/p\| \geq \sum_{h=5k+1}^{Lk} \|sh/p\| \geq \frac{1}{2\pi} \sum_{h=5k+1}^{Lk} (1 - \Re(e(sh/p)))$$

$$= \frac{1}{2\pi}((L-5)k - \Re(\sum_{h=5k+1}^{Lk} e(sh/p))).$$

We further have

$$|\Re(\sum_{h=5k+1}^{Lk} e(sh/p))| \leq |\sum_{h=5k+1}^{Lk} e(sh/p)| \leq \frac{2}{2|\sin(\pi s/p)|},$$

and since $|s|$ is less than $p/2$, we have

$$|\Re(\sum_{h=5k+1}^{Lk} e(sh/p))| \leq \frac{p}{2|s|} \leq (L-6)k.$$

We thus have

$$\sum_{a\in\mathcal{A}} \|sa/p\| \geq k/(2\pi) \geq 2,$$

as soon as p is sufficiently large.

This ends the proof of Theorem 2.

6 Concluding remarks In order to get a result of the type $\sum_{a\in\mathcal{A}} \|\frac{as}{p}\| < 1 + \Omega(p^{-1/2})$, we need, with our construction, to have an upper bound for $\mathrm{Card}(\mathcal{A})$ of the type $c\sqrt{p}$ with $c < 2$, and we believe that when c tends to 2, such a result cannot be valid.

In the other direction, we conjecture that, in Theorem 1, the upper bound for the error term may replaced by $O(p^{-1/2})$. However, our construction may be adapted to show that such an error term cannot be valid when $\mathrm{Card}(\mathcal{A}) = o(p^{-1/2})$.

References

[1] Deshouillers, J-M., Freiman, G. A., When subset sums do not cover all the residues modulo p