Appendix A
Appendix

Proof of Theorem 2.8

As it was mentioned after the statement of Theorem 2.8 it suffices to show that the operator T_m is of weak type (1,1), that is, there exists $c_1 > 0$ such that for every $f \in L^1(\mathbb{R}^n)$

$$\sup_{\alpha>0} \alpha\,|\{x \in \mathbb{R}^n \,:\, |T_m f(x)| > \alpha\}| \le c_1\,\|f\|_1. \tag{A.1}$$

To establish (A.1) we need the Calderón–Zygmund decomposition of L^1-functions.

Lemma A.1 (Calderón–Zygmund lemma). *Let $f \in L^1(\mathbb{R}^n)$. For any $\alpha > 0$, f can be decomposed as*

$$f = g + b = g + \sum_{j=1}^{\infty} b_j \tag{A.2}$$

such that

$$|g(x)| \le 2^n\,\alpha \qquad a.e \qquad x \in \mathbb{R}^n, \tag{A.3}$$

$$b_j \;\; \textit{is supported in a cube} \;\; Q_j, \;\; \textit{with} \; \int_{Q_j} b_j\,dx = 0, \tag{A.4}$$

$$\textit{the} \;\; Q_j \; \textit{have disjoint interior,} \qquad \sum_{j=1}^{\infty} |Q_j| \le \alpha^{-1}\,\|f\|_1, \tag{A.5}$$

and

$$\|g\|_1 + \sum_{j=1}^{\infty} \|b_j\|_1 \le 6\,\|f\|_1. \tag{A.6}$$

Proof. Assume $f \geq 0$ (otherwise $f = f^+ - f^-$ and decompose each part). Since $f \in L^1(\mathbb{R}^n)$ there exists l such that $|Q|^{-1} \int_Q f\,dy < \alpha$ for any cube of side length l.

Divide $\mathbb{R}^n$ into a mesh of cubes of side length l parallel to the axes. Let Q^0 be one of them. Divide each side of Q^0 in two to get 2^n cubes of side length $l/2$. Let Q^1 be such a cube there are two possibilities:

$$\text{(a)} \quad \frac{1}{|Q^1|}\int_{Q^1} f\,dy < \alpha \qquad \text{or} \qquad \text{(b)} \quad \frac{1}{|Q^1|}\int_{Q^1} f\,dy \geq \alpha.$$

In case (b) one stops the subdivision, noticing that

$$\alpha \leq \frac{1}{|Q^1|}\int_{Q^1} f\,dy \leq \frac{2^n}{|Q^0|}\int_{Q^0} f\,dy \leq 2^n\alpha, \tag{A.7}$$

and collecting it in a sequence Q_j.

In case (a) the subdivision process continues. Thus, if $x \notin \bigcup_j Q_j$ it follows from the Lebesgue differentiation theorem (Exercise 2.6 (ii)) that

$$f(x) \leq \alpha \qquad \text{a.e.} \quad x \in \mathbb{R}^n \setminus \cup_j Q_j. \tag{A.8}$$

Finally, we define

$$g(x) = \begin{cases} \dfrac{1}{|Q_j|}\displaystyle\int_{Q_j} f\,dy & \text{if } x \in Q_j, \\ \\ f(x) & \text{if } x \notin Q_j, \end{cases} \tag{A.9}$$

and

$$b_j(x) = (f(x) - g(x))\chi_{Q_j}(x), \quad j \in \mathbb{Z}^+, \tag{A.10}$$

which yields the result. □

We shall denote by Q_j^* the cube having the same center as Q_j and twice its side length as

$$\Omega = \cup_j Q_j \qquad \text{and} \qquad \Omega^* = \cup_j Q_j^* \tag{A.11}$$

with

$$|\Omega^*| \leq \sum_j |Q_j^*| = 2^n \sum_j |Q_j|. \tag{A.12}$$

Proof of inequality (A.1). First we notice that using Calderón–Zygmund Lemma

$$\begin{aligned}&|\{x\in\mathbb{R}^n\,:\,|T_m f(x)|>\alpha\}|\\&\le|\{x\in\mathbb{R}^n\,:\,|T_m g(x)|>\alpha/2\}|+|\{x\in\mathbb{R}^n\,:\,|T_m b(x)|>\alpha/2\}|\\&\le|\{x\in\mathbb{R}^n\,:\,|T_m g(x)|>\alpha/2\}|+|\{x\notin\Omega^*\,:\,|T_m b(x)|>\alpha\}|+|\Omega^*|\\&=E_1+E_2+E_3.\end{aligned}\tag{A.13}$$

From (A.12) and (A.5) in Calderón–Zygmung Lemma we have that

$$E_3=|\Omega^*|\le 2^n\sum_j|Q_j|\le 2^n\alpha^{-1}\|f\|_1.\tag{A.14}$$

Tchebychev's inequality and (A.3) in the Calderón–Zygmund lemma yield

$$\begin{aligned}E_1&=|\{x\in\mathbb{R}^n\,:\,|T_m g(x)|>\alpha/2\}|\le c\Big(\frac{\|T_m g\|_2}{\alpha/2}\Big)^2\le c\,\frac{\|g\|_2^2}{\alpha^2}\\&\le\frac{c}{\alpha^2}\|g\|_1\,\|g\|_\infty\le\frac{c}{\alpha}\|g\|_1\le\frac{c}{\alpha}\|f\|_1.\end{aligned}\tag{A.15}$$

Hence it remains to prove that

$$E_2=|\{x\notin\Omega^*\,:\,|T_m b(x)|>\alpha/2\}|\le c\alpha^{-1}\,\|f\|_1.\tag{A.16}$$

It will suffice to show that

$$\int_{x\notin Q_j^*}|T_m b_j(x)|\,dx\le c\|b_j\|_1,\qquad j\in Z^+.\tag{A.17}$$

To establish (A.17) we follow the argument in [Sg].

Let $\varphi\in C_0^\infty(\{\xi\,:\,|\xi|<2\})$ such that $\varphi(\xi)=1$ for $|\xi|\le 1$. Let $\beta(\xi)=\varphi(\xi)-\varphi(2\xi)$. Thus

$$\sum_{l=-\infty}^{\infty}\beta(2^{-l}\xi)=1\qquad\text{for }\ \xi\neq 0.\tag{A.18}$$

If $m_l(\xi)=\beta(\xi)\,m(2^l\xi)$, then by hypothesis (2.18) it follows that

$$\int|(1-\Delta)^{s/2}m_l(\xi)|^2\,d\xi<c.\tag{A.19}$$

Thus by Plancherel's identity using the notation $K_l(x)=\widehat{m}_l(x)$, one gets that

$$\int(1+|x|^2)^s|K_l(x)|^2\,dx<c,\tag{A.20}$$

which combined with the Cauchy–Schwarz inequality yields the estimate

$$\int_{\{x:\,\max_m|x_m|>R\}}|K_l(x)|\,dx<c\,R^{n/2-s},\tag{A.21}$$

which is a good estimate for $R >> 1$.

Reapplying the estimates (A.19)–(A.20) for $\xi_k m_l(\xi)$ instead of $m_l(\xi)$ one finds that

$$\int |\nabla K_l(x)|\,dx < c. \tag{A.22}$$

Consequently, it follows that

$$\int |K_l(x+y) - K_l(x)|\,dx < c|y|. \tag{A.23}$$

We observe that as a temperate distribution,

$$K(x) = \sum_{l=-\infty}^{\infty} 2^{nl} K_l(2^l x) = \sum_{l=-\infty}^{\infty} \widehat{m}_l(2^{-l}x). \tag{A.24}$$

Assume that Q_j is a cube of side R centered at the origin. From (A.21) one has that

$$\begin{aligned}\int\limits_{x\notin Q_j^*} |2^{nl}K_l(2^l\cdot) * b_j|\,dx &\le \int\limits_{Q_j}\int\limits_{x\notin Q_j^*} |2^{nl}K_l(2^l(x-y))||b_j(y)|\,dxdy\\ &\le \|b_j\|_1 \int\limits_{\{x:\,\max\limits_m |x_m|\ge 2^l R\}} |K_l(x)|\,dx\\ &\le c\,(2^l R)^{n/2-s}\,\|b_j\|_1.\end{aligned} \tag{A.25}$$

Now using that $\int\limits_{Q_j} b_j dy = 0$ it follows that

$$\begin{aligned}&\int\limits_{x\notin Q_j^*} 2^{nl} \int\limits_{y\in Q_j} K_l(2^l(x-y))b_j(y)\,dydx\\ &\quad= \int\limits_{x\notin Q_j^*} 2^{nl} \int\limits_{y\in Q_j} \Big(K_l(2^l(x-y)) - K_l(2^l x)\Big)\,b_j(y)\,dydx.\end{aligned} \tag{A.26}$$

Therefore, (A.23) yields

$$\begin{aligned}&\int\limits_{x\notin Q_j^*} |2^{nl}K_l(2^{nL}\cdot) * b_j|\,dx\\ &\quad\le \int\limits_{y\in Q_j}\int\limits_{x\notin Q_j^*} 2^{nl}|K_l(2^l(x-y)) - K_l(2^l x)||b_j(y)|\,dxdy\\ &\quad\le c\,(2^l R)\|b_j\|_1.\end{aligned} \tag{A.27}$$

Adding in l in (A.25) for $2^l R > 1$ and in (A.27) for $2^l R \le 1$ one gets that

$$\int_{x \notin Q_j^*} |T_m b_j(x)|\, dx \le c\, \|b_j\|_1, \tag{A.28}$$

which completes the proof. □

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