An endpoint Strichartz estimate in spherical coordinates

Harmonic Analysis and Nonlinear Partial Differential Equations

Cho, Yonggeun; Hwang, Gyeongha; Lee, Sanghyuk

数理解析研究所講究録別冊 = RIMS Kokyuroku Bessatsu

2012-07

http://hdl.handle.net/2433/196259

Departmental Bulletin Paper

Kyoto University
An endpoint Strichartz estimate in spherical coordinates

Yonggeun Cho

Department of Mathematics, and Institute of Pure and Applied Mathematics
Chonbuk National University
Jeonju 561-756, Republic of Korea
e-mail: changocho@jbnu.ac.kr

Gyeongha Hwang

Department of Mathematics, POSTECH
Pohang 790-784, Republic of Korea
e-mail: gyeonghahwang@gmail.com

Sanghyuk Lee

Department of Mathematical Sciences, Seoul National University
Seoul 151-747, Republic of Korea
e-mail: shklee@snu.ac.kr

Abstract

We study Strichartz estimates in spherical coordinates for dispersive equations which are defined by spherically symmetric pseudo-differential operators. We extend the recent results in [7, 11] to include more general class of dispersive equations. We use a bootstrapping argument based on various weighted Strichartz estimates.
1 Introduction

In this paper we consider the Cauchy problem of linear dispersive equations:

\[ iu_t - \omega(|\nabla|)u = 0 \quad \text{in } \mathbb{R}^{1+n}, \quad u(0) = \varphi \quad \text{in } \mathbb{R}^n, \quad n \geq 2 \tag{1.1} \]

where \(|\nabla| = \sqrt{-\Delta}\) and the operator \(\omega(|\nabla|)\) is the pseudo-differential operator of which multiplier is \(\omega(|\xi|)\). We will work with \(\omega \in C[0, \infty) \cap C^\infty(0, \infty)\) which satisfies the following properties:

(i) \(\omega'(\rho) > 0\), and either \(\omega''(\rho) > 0\) or \(\omega''(\rho) < 0\) for all \(\rho > 0\),

(ii) \(\omega^{(k)}(\rho_1) \sim \omega^{(k)}(\rho_2), k = 1, 2\) for \(0 < \rho_1 < \rho_2 < 2\rho_1\),

(iii) \(\rho|\omega^{(k+1)}(\rho)| \lesssim |\omega^{(k)}(\rho)|\) for all \(k \geq 1\) and \(\rho > 0\).

Typical examples of \(\omega\) are \(\rho^a(0 < a \neq 1)\), \(\sqrt{1+\rho^2}\), \(\rho\sqrt{1+\rho^2}\), and \(\rho \overline{\sqrt{1+\rho^2}}\) which describe the Schrödinger type equations (see [12] for \(a < 2\)), Klein-Gordon or semirelativistic [8], iBq, and imBq equations. (For the last two see [3] and references therein.)

The solution can formally be written by

\[ u(t, x) = \frac{1}{(2\pi)^n} \int_{\mathbb{R}^n} e^{i(x \cdot \xi - t\omega(|\xi|))} \hat{\varphi}(\xi) \, d\xi. \]

Here \(\hat{\varphi}\) is the Fourier transform of \(\varphi\) defined by \(\int_{\mathbb{R}^n} e^{-ix \cdot \xi} \varphi(x) \, dx\). In [6] the standard Strichartz estimate in \(L^q_tL^p_x\) was considered with \(\omega\) satisfying (i), (ii), (iii) and the following was shown: if \(n \geq 1\) and the pair \((q, p)\) satisfies that \(2 \leq q, p \leq \infty\), \(\frac{1}{q} \leq \frac{n}{2} (\frac{1}{2} - \frac{1}{p})\) and \((q, p) \neq (2, \infty)\), then

\[ \|\nabla|^{s}D^{s_1, s_2}_\omega u\|_{L^q_tL^p_x} \lesssim \|\varphi\|_{L^2_x} \tag{1.2} \]

for \(s_1 = \frac{1}{q} - s_2, \ s_2 = \frac{1}{mq}\) and \(s = \frac{2}{q} - n(\frac{1}{2} - \frac{1}{p})\), where \(D^{s_1, s_2}_\omega\) is a pseudo-differential operator whose symbol is

\[ \left( \frac{\omega'(|\xi|)}{|\xi|} \right)^{s_1} \left| \omega''(|\xi|) \right|^{s_2}. \]

In this paper we study the estimate (1.2) by making use of mixed norm spaces given in the spherical coordinates. For this purpose we use the time-space norm given by

\[ \|f\|_{L^p_tL^\ell_x} = \left( \int_0^\infty \left( \int_{S^{n-1}} |f(r\sigma)|^\ell \, d\sigma \right)^{\frac{p}{\ell}} r^{n-1} \, dr \right)^{\frac{1}{p}}, \quad 1 \leq p, \ell \leq \infty. \]

For simplicity we denoted the spaces \(L^p(r^{n-1} \, dr)\) by \(L^p_r\). Clearly \(\|f\|_{L^\ell_x} = \|f\|_{L^\ell_rL^\ell_x}\). Then let us define several function spaces of Sobolev type. Let \(\Delta_\sigma\) be the Laplace-Beltrami
operator defined on the unit sphere and set $D_\sigma = \sqrt{1 - \Delta_\sigma}$. For $|s| < n/p$, $\gamma \in \mathbb{R}$, we denote by $\dot{H}^{s,p}_r H^{\gamma,\ell}_{\sigma}$ the space
\[
\left\{ f \in S' : \|f\|_{\dot{H}^{s,p}_r H^{\gamma,\ell}_{\sigma}} \equiv \|\nabla|^s D_\sigma^{\gamma} f\|_{L^p_r L^\ell_\sigma} < \infty \right\}.
\]
It should be noted that $C_0^\infty$ is dense in $\dot{H}^{s,p}_r H^{\gamma,\ell}_{\sigma}$ since $|s| < n/p$ (see [2]). We also use spaces equipped with the time-space norm
\[
\|v\|_{L^q_r H^{\gamma,\ell}_{\sigma}} = \left( \int_{\mathbb{R}} \|v(\cdot, t)\|_{H^{s,p}_r H^{\gamma,\ell}_{\sigma}}^q \, dt \right)^{\frac{1}{q}}, 1 \leq q \leq \infty.
\]
If $\ell = 2$, we use a simplified notation $\dot{H}^{s}_{r} H^{\gamma}_{\sigma}$ for $\dot{H}^{s,2}_{r} H^{\gamma,2}_{\sigma}$.

It is well known that the range of $p, q$ for (1.2) can not be extended as it can be shown by Knapp’s example. There have been results [7, 15, 16] which extend the range by allowing loss of angular regularity (also see [9, 13, 14] for related results). Such results have been proven to be useful in the study of various nonlinear equations [1, 7]. Recently in [11] the authors showed that if $n \geq 2$, \[
\frac{1}{q} < (n-1)(\frac{1}{2} - \frac{1}{p}) \text{ or } (q, p) = (\infty, 2)
\]
for $p, q \geq 2$ and $(q, p) \neq (\infty, \infty), (2, \infty)$, then
\[
\||\nabla|^s u\|_{L^2_r L^p_x} \lesssim \|\varphi\|_{L^2_r H^\gamma_x} \tag{1.4}
\]
for $\omega(\rho) = \rho^a$, $a > 0$, $s = \frac{n}{q} - n(\frac{1}{2} - \frac{1}{p})$ and $\gamma \geq 1/q$. They utilized Rodnianski’s argument in [15] and weighted Strichartz estimates (see [5, 7, 1]).

In this short note we show that the estimate (1.3) can be extended to include more general $\omega$ and the angular regularity can be improved (see Proposition 3.1 below). For simplicity we consider only the endpoint case $q = 2$ since the full estimate can be obtained by interpolation with the trivial estimate $\|u\|_{L^\infty_r L^2_x} \lesssim \|\varphi\|_{L^2_x}$ or the estimates in Theorem 1.7 of [11]. The novelty here is the use of bootstrapping to extend the range of (1.4).

The following is our main result.

Theorem 1.1. Suppose that $\omega$ satisfies the conditions (i) – (iii). Let $n \geq 3$, $\frac{2(n-1)}{n-2} < p < \frac{2n}{n-2}$ and $s_0 = \frac{1}{2} - \frac{n-1}{(n-2)p}$. Then for sufficiently small $\varepsilon > 0$ we have
\[
\||\nabla|^s D_\omega^{s_1,s_2} u\|_{L^2_r L^p_x} \lesssim \|\varphi\|_{L^2_r H^\gamma_x} \tag{1.4}
\]
for $s = \frac{n}{p} - \frac{n-2}{2}$, $s_1 = \frac{1}{2} - s_0 - \varepsilon$, $s_2 = s_0 + \varepsilon$ and $\gamma > \frac{1}{2} - ns_0$.

If $\omega(\rho) = \rho^a, 0 < a \neq 1$, then since $\omega'(\rho)/\rho \sim \omega''(\rho) \sim \rho^{a-2}$, we get (1.3) with $\gamma$ as in Theorem 1.1. We will not pursue the optimality of angular regularity, which is another interesting issue.
For the proof of the theorem we use bootstrapping argument based on the Sobolev inequality and weighted Strichartz estimates in spherical coordinates. We will start bootstrapping from the endpoint Strichartz estimate. Once we have an endpoint estimate (1.4) for \( p \neq \infty \), making use of Sobolev inequalities (2.1), (2.2) and (2.3), we get the estimate (1.4) for \( p = p_k, k = 1, 2, 3, \ldots \), successively. The sequence \( p_k \) decreasingly converges to \( \frac{2(n-1)}{n-2} \). Regardless of \( \omega \), by this argument we can get estimate (1.4) arbitrarily close to \( p = \frac{2(n-1)}{n-2} \) and thus via interpolation we also get the estimate
\[
\| |x|^a \nabla |x|^{a-rac{n}{2}} D_{\omega}^{\alpha} f \|_{L^p_{x} L^q_{\omega}} \lesssim \| f \|_{L^2_{x} L^r_{\omega}}.
\]
(2.1)

In [2], the cases \( f \in L^p_{x} \), \( 1 \leq p < 2 \) were treated. Using complex interpolation between (2.1) and the trivial estimates \( \| f \|_{L^p_{x} L^\infty_{\omega}} \lesssim \| f \|_{L^p_{x} L^q_{\omega}} \) and \( \| f \|_{L^\infty_{x} L^2_{\omega}} \lesssim \| f \|_{L^p_{x} L^2_{\omega}} \), we get for

\[\text{Acknowledgements}\]

Y. Cho and G. Hwang were supported by NRF grant No. 2010-0007550 and S. Lee was supported in part by NRF grant No. 2011-0001251 (Korea).

2 Weighted estimates

We first recall Sobolev inequality which was introduced in [4] and extended in [7]. Let \( 0 < a < \frac{n-1}{2} \) and \( \alpha \leq \frac{n-1}{2} - a \). Then
\[
\| |x|^a \nabla |x|^{a-rac{n}{2}} D_{\sigma}^{\alpha} f \|_{L^p_{x} L^q_{\omega}} \lesssim \| f \|_{L^2_{x} L^\infty_{\omega}}.
\]
(2.1)
\[ 2 \leq \ell \leq \infty \]
\[ \|x\|^{\frac{2a}{\ell}} |\nabla|^\frac{2}{\ell}(a-\frac{n}{2}) D_{\sigma}^{\frac{2}{\ell}(\alpha-a)} f \|_{L_{r}^{\infty} L_{\sigma}^{\ell}} \leq C_{0} \|f\|_{L_{x}^{\ell}}, \quad (2.2) \]
\[ \|x\|^{\frac{2a}{\ell}} |\nabla|^\frac{2}{\ell}(a-\frac{n}{2}) D_{\sigma}^{\frac{2}{\ell}(\alpha-a)} f \|_{L_{r}^{\infty} L_{\sigma}^{2}} \leq C_{0} \|f\|_{L_{x}^{\ell} L_{\sigma}^{2}}, \quad (2.3) \]

Replacing \( f \) of (2.2) with \( u \) and applying endpoint Strichartz estimate (1.2), we obtain the following.

**Lemma 2.1.** Let \( n \geq 3 \), \( 0 < a < \frac{n-1}{2} \) and \( \alpha \leq \frac{n-1}{2} - a \). Then

\[ \|x|^{\frac{a}{n}(1-\frac{2}{n})} |\nabla|^{(a-\frac{n}{2})(1-\frac{2}{n})} \mathcal{D}_{\omega}^{\frac{n-1}{2n}} D_{\sigma}^{\frac{1}{2n}} u \|_{L_{t}^{2} L_{r}^{\infty} L_{\sigma}^{\frac{2n}{n-2}}} \leq C_{0}' \|\varphi\|_{L_{x}^{\infty}}. \quad (2.4) \]

**Proof.** From (2.2) with \( \ell = \frac{2n}{n-2} \) and Hölder’s inequality it follows that

\[ \|x|^{a(1-\frac{2}{n})} |\nabla|^{(a-\frac{n}{2})(1-\frac{2}{n})} \mathcal{D}_{\omega}^{\frac{n-1}{2n}} D_{\sigma}^{\frac{1}{2n}} u \|_{L_{t}^{2} L_{r}^{\infty} L_{\sigma}^{\frac{2n}{n-2}}} \leq C_{0} \|\mathcal{D}_{\omega}^{\frac{n-1}{2n}} D_{\sigma}^{\frac{1}{2n}} u \|_{L_{t}^{2} L_{r}^{\infty} L_{\sigma}^{\frac{2n}{n-2}}}, \]

where \( c_{n} \) depends only on \( n \). Then the estimate (1.2) with \( \ell = \frac{2n}{n-2} \) gives (2.4). \( \square \)

We will use the following \( L_{t}^{2} L_{x}^{2} \) estimate.

**Lemma 2.2.** Let \( -n/2 < b < -1/2 \) and \( \beta \leq -\frac{1}{2} - b \). Then we have

\[ \|x|^{b} |\nabla|^{b+1} \mathcal{D}_{\omega}^{\frac{1}{2},0} D_{\sigma}^{\beta} u \|_{L_{t}^{2} L_{r}^{2}} \leq C_{1} \|\varphi\|_{L_{x}^{\infty}}. \quad (2.5) \]

For (2.5) we refer to [1] and also to [5, 7] for earlier versions.

### 3 Proof of Theorem 1.1

In this section we prove Theorem 1.1 by showing Proposition 3.1. It will be shown via bootstrapping argument which makes use of weighted Strichartz estimates introduced in the previous section.

**Proposition 3.1.** Let \( \omega \) satisfy (i) – (iii) and \( n \geq 3 \). Then, for \( \frac{2(n-1)}{n-2} < p < \infty \),

\[ \|D_{\omega}^{\frac{1}{2},0} D_{\sigma}^{\frac{n-2}{2} - \frac{n-1}{p}} u \|_{L_{t}^{p} L_{r}^{2}} \lesssim \|\varphi\|_{L_{x}^{\infty}}. \quad (3.1) \]
Assuming this for the moment, we prove Theorem 1.1. In fact, using (3.1) and Sobolev embedding $(H^{(n-1)/2-1/p}_r \hookrightarrow L^p_r)$ on the unit sphere, we have for $\frac{2(n-1)}{n-2} < p < \infty$
\begin{align*}
\|\nabla^{s}D_{\omega}^{\ell,0}u\|_{L^{2}_{r}L^{p}_{r}} & \lesssim \| \varphi \|_{L^{2}_{r}H^{\ell}_{\sigma}},
\end{align*}
where $s = \frac{n}{p} - \frac{n-2}{2}$. Now, from the endpoint estimate of (1.2) we have
\begin{align*}
\|\nabla^{\frac{1}{2}-\frac{1}{2n}}D_{\omega}D_{\sigma}^{\frac{1}{2},0}u\|_{L^{2}_{r}L^{\frac{2n}{2n-2}}_{r}} & \lesssim \| \varphi \|_{L^{2}_{r}H^{0}_{\sigma}}.
\end{align*}
Interpolation between these two estimates gives the desired result.

Now it remains to prove Proposition 3.1.

### 3.1 Bootstrapping

We start with interpolating (2.4) with $\alpha = (n-1)/2 - a$ and (2.5) with $\beta = -1/2 - b$. So, we have for $2 \leq p_{1} \leq \infty$
\begin{align*}
\| |x|^{c_{1}}|\nabla|^{d_{1}}D_{\omega}^{\delta_{1},\delta_{1}'}D_{\sigma}^{\gamma_{1}}u\|_{L^{2}_{r}L^{p_{1}}_{r}(L^{2}_{\sigma} \cap L^{\ell_{1}}_{\sigma})} & \leq C_{1}\| \varphi \|_{L^{2}_{r}},
\end{align*}
where $C_{1} = C_{0}^{1-\theta_{1}}C_{1}^{\theta_{1}}$, $\theta_{1} = 2/p_{1}$, and
\begin{align*}
c_{1} & = a(1 - 2/n)(1 - 2/p_{1}) + 2b/p_{1}, \\
d_{1} & = c_{1} - (n-2)/2 + n/p_{1}, \\
\delta_{1} & = \frac{1}{n}(-\frac{1}{2} + \frac{1}{p_{1}}), \\
\delta_{1}' & = \frac{1}{n}(\frac{1}{2} - \frac{1}{p_{1}}), \\
\gamma_{1} & = \frac{n^{2} - 3n + 2}{2n} - \frac{n^{2} - 2n + 2}{np_{1}} - c_{1}, \\
\frac{1}{\ell_{1}} & = \frac{n-2}{2n} + \frac{1}{np_{1}}.
\end{align*}
We call it the first stage estimate and will proceed similarly by combining the resulting estimate and (2.5). At every stage we choose the indices $c_{k}, k \geq 1$ to be 0. In view of the range of $a$ and $b$ we can take $c_{1} = 0$ when $p_{1}$ satisfies that $2 + \frac{2n}{(n-1)(n-2)} = p_{0} < p_{1} < \infty$. In particular, such $p_{1}$ gives
\begin{align*}
\| |x|^{\frac{2a}{p_{1}}}|\nabla|^{\frac{2}{p_{1}a}+d_{1}'}D_{\omega}^{\delta_{1},\delta_{1}'}D_{\sigma}^{\gamma_{1}}u\|_{L^{2}_{r}L^{p_{1}}_{r}(L^{2}_{\sigma} \cap L^{\ell_{1}}_{\sigma})} & \leq C_{1}\| \varphi \|_{L^{2}_{r}},
\end{align*}
We use it in the place of Strichartz estimate (1.2). Now, from the estimates (2.3) and (3.3) it follows that
\begin{align*}
\| |x|^{\frac{2a}{p_{1}}}|\nabla|^{\frac{2a}{p_{1}}(a-\frac{n}{2})+d_{1}'}D_{\omega}^{\delta_{1},\delta_{1}'}D_{\sigma}^{\gamma_{1}+\gamma_{1}}u\|_{L^{2}_{r}L^{p_{1}}_{r}L^{2}_{\sigma}} & \leq C_{0}\| \nabla|^{d_{1}'}D_{\omega}^{\delta_{1},\delta_{1}'}D_{\sigma}^{\gamma_{1}}u\|_{L^{2}_{r}L^{p_{1}}_{r}L^{2}_{\sigma}} \\
& \leq C_{0}C_{1}\| \varphi \|_{L^{2}_{r}},
\end{align*}
where $a$ and $\alpha$ are given in Lemma 2.1. Interpolating this with (2.5) for $\alpha = \frac{n-1}{2} - a$ and $\beta = -b - \frac{1}{2}$, we have the second stage estimate: for $2 \leq p_2 \leq \infty$

$$\| |x|^{c_2} |\nabla|^{d_2} D_\omega^\delta D_\sigma^\gamma u\|_{L_t^2 L_r^{p_2} L_3^2} \leq C_2 \| \varphi \|_{L_x^2},$$

where $C_2 = (C_0C_1)^{1-\theta_2}C_1^{\theta_2}$, $\theta_2 = 2/p_2$ and

$$c_2 = \frac{2a}{p_1} \left( 1 - \frac{2}{p_2} \right) + \frac{2b}{p_2} < \frac{2a}{p_0} \left( 1 - \frac{2}{p_2} \right) + \frac{2b}{p_2},$$
$$d_2 = c_2 + (-\frac{n}{p_1} + d_1)(1 - \frac{2}{p_2}) + \frac{2}{p_2},$$
$$\delta_2 = \delta_1(1 - \frac{2}{p_2}) + \frac{1}{p_2}, \quad \delta_2' = \delta_1'(1 - \frac{2}{p_2}),$$
$$\gamma_2 = (\gamma_1 + \frac{n-1}{p_1})(1 - \frac{2}{p_2}) - \frac{1}{p_2} - c_2.$$

If $2 + \frac{p_0}{n-1} < p_2 < \infty$, then by suitable choices of $a, b$, we can make $c_2 = 0$. Thus $d_2 = -\frac{n-2}{2} + \frac{n}{p_2}$, $\gamma_2 > 0$ and we also have

$$\| |\nabla|^{d_2} D_\omega^\delta D_\sigma^\gamma u\|_{L_t^2 L_r^{p_2} L_3^2} \leq C_2 \| \varphi \|_{L_x^2}.$$

Repeating this procedure $k$ times, we obtain

$$\| |x|^{c_k} |\nabla|^{d_k} D_\omega^\delta D_\sigma^\gamma u\|_{L_t^2 L_r^{p_k} L_3^2} \leq C_k \| \varphi \|_{L_x^2},$$

where $C_k = (C_0C_{k-1})^{1-\theta_k}C_1^{\theta_k}$, $\theta_k = 2/p_k$ and

$$c_k = \frac{2a}{p_{k-1}} \left( 1 - \frac{2}{p_k} \right) + \frac{2b}{p_k},$$
$$d_k = c_k + (-\frac{n}{p_{k-1}} + d_{k-1})(1 - \frac{2}{p_k}) + \frac{2}{p_k},$$
$$\delta_k = \delta_{k-1}(1 - \frac{2}{p_k}) + \frac{1}{p_k}, \quad \delta_k' = \delta_{k-1}'(1 - \frac{2}{p_k}),$$
$$\gamma_k = (\gamma_{k-1} + \frac{n-1}{p_{k-1}})(1 - \frac{2}{p_k}) - \frac{1}{p_k} - c_k.$$

If $p_k$ satisfies that $\tilde{p}_k < p_k < \infty$, where

$$\tilde{p}_k = 2 + \frac{2}{n-1} + \frac{2}{(n-1)^2} + \cdots + \frac{2}{(n-1)^{k-2}} + \frac{p_0}{(n-1)^{k-1}},$$

then we can choose $a, b$, such that $c_k = 0$ and $d_k = -\frac{n-2}{2} + \frac{n}{p_k}$, $\gamma_k > 0$. Thus we have

$$\| |\nabla|^{d_k} D_\omega^\delta D_\sigma^\gamma u\|_{L_t^2 L_r^{p_k} L_3^2} \leq C_k \| \varphi \|_{L_x^2}.$$  (3.4)
3.2 A limiting argument

We first observe that \( \bar{\rho}_k \) is decreasing and \( \bar{\rho}_k \to \frac{2(n-1)}{n-2} \equiv \bar{\rho} \) as \( k \to \infty \). Now we fix \( p \) with \( \bar{\rho} < p < p_0 \) and let \( k \to \infty \) to get the desired estimate (3.1).

Since \( \bar{\rho} < p < p_0 \), \( 1 - \theta_k \) is bound away from 0 and 1, there exists \( 0 < \lambda < 1 \) such that
\[
C_k \leq C_0^{1-\delta_k+(1-\delta_k)(1-\theta_{k-1})+\cdots\prod_{2\leq j\leq k}(1-\theta_j)}C_1 \leq C_0^{\sum_{j=1}^{\infty} \lambda^j}C_0' C_1 = C_0^{1-\lambda}C_0' C_1.
\]
If \( p \) is fixed near \( \frac{2(n-1)}{n-2} \), then we can pick \( p_k = p \) for all \( k \geq k_0 \) for some large \( k_0 \). Since \( \delta_k = \delta_{k-1}(1 - 2/p) + 1/p \) for \( k \geq k_0 \), \( \delta_k \) is increasing and bounded and thus \( \lim_{k \to \infty} \delta_k = \frac{1}{2} \). Also \( \delta'_k/\delta'_{k-1} = (1 - 2/p) \) implies \( \delta'_k \to 0 \) as \( k \to \infty \). On the other hand, \( \gamma_k \) is decreasing and bounded below so that \( \gamma_k \to \frac{n-2}{2} - \frac{n-1}{p} \). This limit goes to 0 as \( p \to \frac{2(n-1)}{n-2} \).

By the usual density argument, for the proof of (3.1) we may assume \( \hat{\varphi} \in C_0^\infty(\mathbb{R}^n \setminus \{0\}) \). Since \( |\nabla|^{d_k} D_\omega^{\delta_k} D_\sigma^{\gamma_k} u \) and \( |\nabla|^{-\frac{n-2}{2} + \frac{n}{p}} D_\omega^{\frac{1}{2},0} D_\sigma^{\frac{n-2}{2} - \frac{n-1}{p}} u \) are smooth and have the same compact Fourier support, it is easy to see that both are \( O((|x| + 1)^{-M}(|t| + 1)^{-M}) \) for any large \( M \). Then it is obvious that
\[
\lim_{k \to \infty} \left| \nabla |^{d_k} D_{\omega}^{\delta_k} D_\sigma^{\gamma_k} u \right| = \left| \nabla |^{-\frac{n-2}{2} + \frac{n}{p}} D_{\omega}^{\frac{1}{2},0} D_\sigma^{\frac{n-2}{2} - \frac{n-1}{p}} u \right|.
\]
Hence by taking limit
\[
\lim_{k \to \infty} \left\| \nabla |^{d_k} D_{\omega}^{\delta_k} D_\sigma^{\gamma_k} u \right\|_{L_t^2 L_r^p L_\sigma^2} = \left\| \nabla |^{-\frac{n-2}{2} + \frac{n}{p}} D_{\omega}^{\frac{1}{2},0} D_\sigma^{\frac{n-2}{2} - \frac{n-1}{p}} u \right\|_{L_t^2 L_r^p L_\sigma^2}.
\]
Since \( C_k \) is uniform on \( k \), from (3.4) we get (3.1) provided that \( p \) is fixed near \( \bar{\rho} \). This completes the proof of Proposition 3.1.

References


