



Title	A maximal inequality associated to Schrödinger type equation.
Author(s)	Cho, Yonggeun; Lee, Sanghyuk; Shim, Yongsun
Citation	Hokkaido University Preprint Series in Mathematics, 685, 1-10
Issue Date	2005
DOI	10.14943/83836
Doc URL	<a href="http://hdl.handle.net/2115/69490">http://hdl.handle.net/2115/69490</a>
Type	bulletin (article)
File Information	pre685.pdf



[Instructions for use](#)

# A MAXIMAL INEQUALITY ASSOCIATED TO SCHRÖDINGER TYPE EQUATION

YONGGEUN CHO, SANGHYUK LEE, AND YONGSUN SHIM

ABSTRACT. In this note, we consider a maximal operator  $\sup_{t \in \mathbb{R}} |u(x, t)| = \sup_{t \in \mathbb{R}} |e^{it\Omega(D)} f(x)|$ , where  $u$  is the solution to the initial value problem  $u_t = i\Omega(D)u$ ,  $u(0) = f$  for a  $C^2$  function  $\Omega$  with some growth rate at infinity. We prove that the operator  $\sup_{t \in \mathbb{R}} |u(x, t)|$  has a mapping property from a fractional Sobolev space  $H^{\frac{1}{4}}$  with additional angular regularity to  $L_{loc}^2$ .

## 1. INTRODUCTION

We consider the almost everywhere convergence problem on the free Schrödinger type equation:

$$\frac{\partial}{\partial t} u(x, t) = i\Omega(D)u(x, t) \quad \text{in } \mathbb{R}^{n+1} (n \geq 2), \quad u(x, 0) = f(x),$$

where  $\Omega(D)$  is a generalized differential operator defined by a  $C^2$  function  $\Omega$  and  $D = (-\Delta)^{\frac{1}{2}}$ . For smooth initial data  $f$ , the solution  $u(x, t) = e^{it\Omega(D)} f$  can be written as

$$u(x, t) = \frac{1}{(2\pi)^n} \int_{\mathbb{R}^n} e^{i(x \cdot \xi + t\Omega(\xi))} \widehat{f}(\xi) d\xi \quad f \in \mathcal{S}(\mathbb{R}^n),$$

where  $\widehat{f}(\xi) = \int e^{-ix \cdot \xi} f(x) dx$ . In this note, we assume that the initial data  $f$  has  $H^s$  regularity for some  $s > 0$  as well as some regularity in the angular direction. For  $\alpha, \beta \geq 0$ , we define

$$\|f\|_{H^\alpha H_\omega^\beta} := \|(1 - \Delta)^{\frac{\alpha}{2}} f\|_{L_r^2 H_\omega^\beta} < \infty,$$

where  $\|g\|_{L_r^2}^2 = \int_0^\infty |g|^2 r^{n-1} dr$ ,  $\|g\|_{L_r^2 H_\omega^\beta} = \| |(1 - \Delta_\omega)^{\frac{\beta}{2}} f(r\omega) \|_{L_r^2}$  (here,  $(r, \omega) \in \mathbb{R}_+ \times S^{n-1}$  is the spherical coordinates), and  $\Delta_\omega$  is the Laplace-Beltrami operator on  $S^{n-1}$ . Since  $\Delta_\omega$  commutes with  $\Delta$ , one can readily check that  $\|g\|_{H^\alpha H_\omega^\beta} \sim \|(1 - \Delta_\omega)^{\frac{\beta}{2}} g\|_{H^\alpha}$  (for instance, see [9]). Since not every function in  $H^\alpha H_\omega^\beta$  has radial regularity higher than  $\alpha$ , there is no embedding from or into a usual Sobolev space. In particular, it should be noted that  $H^\alpha H_\omega^\beta \not\subseteq H^{\alpha+\gamma}$  ( $0 < \gamma < \beta$ ) and  $H^\alpha H_\omega^\beta \not\supseteq H^{\alpha+\gamma}$  ( $\gamma \geq \beta$ ).

---

2000 *Mathematics Subject Classification.* Primary 42B25; Secondary 42A45.

*Keywords and phrases.* Schrödinger type equation, maximal operator, angular regularity.

The first author was supported by Japan Society for the Promotion of Science under JSPS Postdoctoral Fellowship for Foreign Researchers and the second author was partially supported by the Post-doctoral Fellowship Program of Korea Science & Engineering Foundation (KOSEF).

We also assume that  $\Omega$  is radially symmetric and satisfies

$$c_1|\rho|^{a-k} \leq |\Omega^{(k)}(\rho)| \leq c_2|\rho|^{a-k} \quad (k = 0, 1, 2), \quad \text{if } |\rho| \geq N$$

for some  $c_1, c_2, a > 0$  with  $a \neq 1$  and a large  $N > 0$ . For the point-wise convergence for the averaging on the sphere, it is sufficient to consider boundedness of maximal operator  $u^*(x) = \sup_{t \in \mathbb{R}} |u(x, t)|$ . We prove

**Theorem 1.1.** *For any  $\varepsilon > 0$ , if  $f \in H^{\frac{1}{4}}H_\omega^{\frac{3}{4}+\varepsilon}$ , then there exists a constant  $C$ , depending only on  $\Omega, n, R$ , such that*

$$\|u^*\|_{L^2(B_R)} \leq C\|f\|_{H^{\frac{1}{4}}H_\omega^{\frac{3}{4}+\varepsilon}}.$$

Let  $\chi_R$  be a radial and smooth cut-off function such that  $\chi_R = 1$  on  $B_R$  and 0 on  $B_{2R}^c$ . Let us define for a fixed  $s \in [1/4, 1/2]$ ,

$$Tf(x, t) = \chi_R(x) \int e^{i(x \cdot \xi + t\Omega(\xi))} \widehat{f}(\xi) \frac{d\xi}{(1 + |\xi|^2)^{\frac{s}{2}}},$$

$$T^*f(r) = \sup_{t \in \mathbb{R}} |Tf(x, t)|.$$

Then Theorem 1.1 follows immediately from

**Theorem 1.2.** *For any  $f \in L_r^2 H_\omega^{1+\varepsilon-s}$ , there exists a constant  $C$ , depending only on  $\Omega, n, R, s$ , such that*

$$\|T^*f\|_{L^2} \leq C\|f\|_{L_r^2 H_\omega^{1+\varepsilon-s}}.$$

The maximal function  $u^*$  and operator  $T^*$  have been studied extensively by many authors ([1, 2, 3, 4, 5, 7, 8, 10, 11, 12, 13, 14, 18, 19, 21]). P. Sjölin [14] and L. Vega [19] showed that

$$(1.1) \quad \|u^*\|_{L^2(B_R)} \leq C\|f\|_{H^s},$$

only if  $s \geq \frac{1}{4}$ . However, the sufficiency remains open. Up to now, it is known that (1.1) is true if  $n = 1$  ([5, 8]) or the initial data is radial ([4, 12]), or  $s > \frac{1}{2}$  and  $n \geq 2$  ([11, 19]). Recently, T. Tao [18] obtained (1.1) for  $s > \frac{2}{5}$  and  $n = 2$ .

On the other hand, Theorem 1.1 shows that it is true for  $s = \frac{1}{4}$  if we assume the additional angular regularity. If the initial data is a finite linear combination of radial functions and spherical harmonics, it was proved by the first and third authors in [4] that the conjecture is true for  $s = \frac{1}{4}$  but has a dependency on the order  $k$  of spherical harmonics like  $O((n + 2k)^{n+2k})$ . In this connection, Theorem 1.1 improves the dependency on the order up to  $k^{\frac{3}{4}+\varepsilon}$  (see (2.2) below). In case of a local maximal operator  $\sup_{|t| \leq 1} |u(x, t)|$ , then it was shown by G. Gigante and F. Soria [6] that the angular regularity assumption can be slightly weakened up to  $k^{\frac{1}{2}+\varepsilon}$ . However, we don't know yet whether the angular regularity must be imposed or not.

From the assumption on  $\Omega$ , we treat  $\Omega$  not only of the form  $|\xi|^a$  but also  $\sum_{i=1}^l a_i |\xi|^{m_i}$  for any number  $m_l > m_{l-1} > \dots > m_1$ ,  $m_l \neq 1$  and  $a_i \in \mathbb{R}$ . For another use of angular regularity, we refer to [9] in which endpoint Strichartz estimates of 3-d wave and Klein-Gordon equations are considered.

For the proof of our results, we estimate the maximal operators locally in  $L^2$  since there is neither a global  $L^2$  estimate for  $s \geq \frac{1}{4}$  ([11]), nor a local estimate in  $L^p(p > 2)$  for  $s = \frac{1}{4}$ . We use the asymptotic property of Bessel functions  $J_\nu$  and the spherical harmonic expansion  $f(r\omega) = \sum_k f_k(r)Y_k(\omega)$  where  $Y_k$  are spherical harmonic functions of order  $k$ . As to be shown in the next section, the angular regularity is related to the order of spherical harmonic function  $Y_k(\omega)$  (see (2.1)). By the orthogonality among spherical harmonic functions of different orders, to get Theorem 1.2, the matters are reduced to obtaining uniform estimate along  $k$ . To control the dependency on  $k$ , the angular regularity is used.

If not specified, throughout this paper,  $C$  denotes a generic constant that depends on  $\Omega, n, R, s$ . We use the notation  $A \lesssim B$  and  $A \sim B$  to denote  $|A| \leq CB$  and  $C^{-1}B \leq |A| \leq CB$  respectively.

## 2. PROOF OF THEOREM 1.2

We begin with reviewing some properties of the spherical harmonic expansion. If  $f(r\omega) = g(r)Y_k(\omega)$  for a radial function  $g$  and a spherical harmonic  $Y_k$  of order  $k$ , then we have

$$\widehat{f}(\rho\theta) = G(\rho)Y_k(\theta), \quad \|g\|_{L_r^2} = \|G\|_{L_r^2},$$

where

$$G(\rho) = c_{n,k} \int_0^\infty g(r)r^{n-1}(r\rho)^{-\frac{n-2}{2}} J_\nu(r\rho) dr, \quad |c_{n,k}| \leq C, \quad \nu = \frac{2k+n-2}{2}.$$

For the representation of  $G$ , see e.g. [16] or [22]. Since  $\Delta_\omega Y_k = k(k+n-2)Y_k$ , we also have  $\|f\|_{L_r^2 H_\omega^\beta} \sim (1+k^2)^{\frac{\beta}{2}} \|g\|_{L_r^2} \|Y_k\|_{L_\omega^2}$ . Furthermore, if  $h \in L_r^2 H_\omega^\beta$ , then there exist radial functions  $\{h_k^l\}$  and spherical harmonics  $\{Y_k^l\}$  such that

$$h(r\omega) = \sum_{k \geq 0} \sum_{1 \leq l \leq d(k)} h_k^l(r) Y_k^l(\omega) \quad \text{in } L_r^2 H_\omega^\beta,$$

where  $d(k)$  is the dimension of the space of spherical harmonics of degree  $k$ , and

$$(2.1) \quad \|h\|_{L_r^2 H_\omega^\beta}^2 \sim \sum_{k \geq 0} \sum_{1 \leq l \leq d(k)} (1+k^2)^\beta \|h_k^l\|_{L_r^2}^2 \|Y_k^l\|_{L_\omega^2}^2.$$

Thus from the orthogonality of spherical harmonic functions, we have only to consider the case that  $f(r\omega) = g(r)Y_k(\omega)$ . It is also sufficient for the proof of theorem to show for large  $k$

$$(2.2) \quad \|T^* f\|_{L^2} \lesssim k^{\frac{1}{2}-s} \|g\|_{L_r^2} \|Y_k\|_{L_\omega^2},$$

since  $k^{\frac{1}{2}-s} \|g\|_{L_r^2} \|Y_k\|_{L_\omega^2} = k^{1-s+\varepsilon} \|g\|_{L_r^2} \|Y_k\|_{L_\omega^2} \cdot k^{-\frac{1}{2}-\varepsilon}$ .

By scaling and translation, we may assume that  $B_R = B(0, 1)$ , ball with radius 1 centered at the origin. Since  $\widehat{f}(\rho\omega) = G(\rho)Y_k(\omega)$ , from the definition of  $T$ , we have

$$\begin{aligned} Tf(r\omega, t) &= \chi_1(r) \int_{S^{n-1}} \int_0^\infty e^{i(r\omega \cdot \rho\theta + t\Omega(\rho))} G(\rho)Y_k(\theta)\rho^{n-1} \frac{d\rho}{(1+\rho^2)^{\frac{n}{2}}} d\theta \\ &= c_{n,k}\chi_1(r) \int_0^\infty e^{it\Omega(\rho)} (r\rho)^{-\frac{n-2}{2}} J_\nu(r\rho)\rho^{n-1} G(\rho) \frac{d\rho}{(1+\rho^2)^{\frac{n}{2}}} Y_k(-\omega). \end{aligned}$$

Let us define an operator  $S$  by

$$SG(r, t) = c_{n,k}r^{\frac{n-1}{2}}\chi_1(r) \int_0^\infty e^{it\Omega(\rho)} (r\rho)^{-\frac{n-2}{2}} J_\nu(r\rho)\rho^{n-1} G(\rho) \frac{d\rho}{(1+\rho^2)^{\frac{n}{2}}}.$$

Let us denote by  $\|F\|_{L^p L^q}$  the mixed norm  $\|(\|F(r, t)\|_{L^q(dt)})\|_{L^p(dr)}$ . To prove (2.2) it suffices to show that

$$(2.3) \quad \|S\tilde{G}\|_{L^2 L^\infty} \lesssim k^{\frac{1}{2}-s} \|\tilde{G}\|_{L^2},$$

where  $\tilde{G}(\rho) = \rho^{\frac{n-1}{2}} G(\rho)$ . Now we define the dual operator  $S^d$  of  $S$  by

$$S^d F(\rho) = \frac{c_{n,k}}{(1+\rho^2)^{\frac{n}{2}}} \int_{\mathbb{R}} \int_0^\infty e^{-it\Omega(\rho)} (r\rho)^{\frac{1}{2}} J_\nu(r\rho)\chi_1(r) F(r, t) dr dt$$

for  $F \in C_0^\infty(\mathbb{R}_+ \times \mathbb{R})$ . Then, by duality (2.3) follows from

$$(2.4) \quad \|S^d F\|_{L^2} \leq Ck^{\frac{1}{2}-s} \|F\|_{L^2 L^1}.$$

Choose smooth cut-off functions  $\phi_0, \phi_1$  and  $\phi_3$  so that  $\phi_0 = 1$  on  $\{|s| < \frac{1}{2}\}$ ,  $\phi_0 = 0$  on  $\{|s| > 1\}$ ,  $\phi_1 = 1$  on  $\{|s| \sim 1\}$ ,  $\phi_1 = 0$  otherwise,  $\phi_2 = 0$  on  $\{|s| < 2\}$ ,  $\phi_2 = 1$  on  $\{|s| > 3\}$ , and  $\phi_0 + \phi_1 + \phi_2 = 1$ . Then we decompose  $S^d$  as

$$S^d F(\rho) = S_0 F + S_1 F + S_2 F,$$

where for  $i = 0, 1, 2$ ,

$$S_i F(\rho) = \frac{c_{n,k}}{(1+\rho^2)^{\frac{n}{2}}} \int_{\mathbb{R}} \int_0^\infty e^{-it\Omega(\rho)} (r\rho)^{\frac{1}{2}} J_\nu(r\rho)\phi_i\left(\frac{r\rho}{\nu}\right)\chi_1(r) F(r, t) dr dt.$$

Now we need to show each  $S_i$  satisfies (2.4) in the place of  $S^d$ . Each estimate is to be shown using the following asymptotic behavior of Bessel functions:

$$(2.5) \quad |J_\nu(t)| \leq C \exp(-C\nu), \quad \text{if } t \leq \frac{\nu}{2},$$

$$(2.6) \quad \frac{1}{r} \int_0^r |J_\nu(t)|^2 t dt \leq C \quad \text{for all } r > 0,$$

$$(2.7) \quad J_\nu(t)\phi_2\left(\frac{t}{\nu}\right) = t^{-\frac{1}{2}}(b_+ e^{it} + b_- e^{-it})\phi_2\left(\frac{t}{\nu}\right) + \Phi_\nu(t)\phi_2\left(\frac{t}{\nu}\right),$$

where  $|\Phi_\nu(t)| \leq \frac{C}{t}$ ,  $|b_\pm| \leq C$  and the constant  $C$  is independent of  $\nu$ . For the proof of (2.5), see [17]. The mean value estimate (2.6) can be found in Section 4.10 of [20]. Invoking the Schl\"afli's integral representation (see p.176 in [23]):

$$J_\nu(t) = \frac{1}{2\pi} \int_0^{2\pi} e^{i(t \sin \theta - \nu\theta)} d\theta - \frac{\sin(\nu\pi)}{\pi} \int_0^\infty e^{-\nu\tau - t \sinh \tau} d\tau,$$

the last asymptotic behavior follows from the easy estimate

$$\left| \frac{\sin(\nu\pi)}{\pi} \int_0^\infty e^{-\nu\tau - t \sinh \tau} d\tau \right| \leq \frac{C}{\nu + t}$$

and the method of stationary phase such that

$$\frac{1}{2\pi} \int_0^{2\pi} e^{i(t \sin \theta - \nu\theta)} d\theta \sim (b_+ e^{it} + b_- e^{-it}) t^{-\frac{1}{2}} + O(t^{-\frac{3}{2}}) \quad \text{for } t > 2\nu.$$

Using (2.5), we now see

$$\begin{aligned} S_0 F(\rho) &\lesssim \nu^{\frac{1}{2}} e^{-C\nu} (1 + \rho^2)^{-\frac{s}{2}} \int_0^{\min(\frac{\nu}{\rho}, 2)} \|F(r, \cdot)\|_{L^1} dr \\ &\lesssim \nu^{\frac{1}{2}} e^{-C\nu} (1 + \rho^2)^{-\frac{s}{2}} (\min(\frac{\nu}{\rho}, 2))^{\frac{1}{2}} \|F\|_{L^2 L^1}. \end{aligned}$$

Thus we have

$$(2.8) \quad \begin{aligned} \|S_0 F\|_{L^2} &\lesssim \nu^{\frac{1}{2}} e^{-C\nu} \left( \int_0^\infty (1 + \rho^2)^{-s} \min(\frac{\nu}{\rho}, 2) d\rho \right)^{\frac{1}{2}} \|F\|_{L^2 L^1} \\ &\lesssim \nu^{\frac{1}{2}-s} e^{-C\nu} \|F\|_{L^2 L^1}. \end{aligned}$$

For  $S_1$ , we have

$$|S_1 F(\rho)| \lesssim (1 + \rho^2)^{-\frac{s}{2}} \left( \int_0^2 J_\nu^2(r\rho) r \rho \phi_1^2\left(\frac{r\rho}{\nu}\right) dr \right)^{\frac{1}{2}} \|F\|_{L^2 L^1}.$$

By the change of variable  $r \mapsto r/\rho$ , the integral in the RHS of the above estimate is bounded by  $\frac{1}{\rho} \int_0^{2\rho} J_\nu^2(r) r \phi_1^2(r/\nu) dr$ . Since  $\rho \geq \frac{\nu}{4}$  from the support condition of  $\phi_1$ , by (2.6) we have

$$|S_1 F(\rho)| \leq C \nu^{\frac{1}{2}} (1 + \rho^2)^{-\frac{s}{2}} \rho^{-\frac{1}{2}} \chi_{\{\rho \geq \frac{\nu}{4}\}} \|F\|_{L^2 L^1}.$$

We thus obtain

$$(2.9) \quad \|S_1 F\|_{L^2} \lesssim \nu^{\frac{1}{2}-s} \|F\|_{L^2 L^1}.$$

Now we estimate  $S_2 F$ . Let us set  $S_2 F = S_+ F + S_- F + S_3 F$ , where

$$\begin{aligned} S_\pm F(\rho) &= \frac{c_{n,k} b_\pm}{(1 + \rho^2)^{\frac{s}{2}}} \int_{\mathbb{R}} \int_0^\infty e^{i(\pm r\rho - t\Omega(\rho))} \phi_2\left(\frac{r\rho}{\nu}\right) \chi_1(r) F(r, t) dr dt \\ S_3 F(\rho) &= \frac{c_{n,k}}{(1 + \rho^2)^{\frac{s}{2}}} \int_{\mathbb{R}} \int_0^\infty e^{-it\Omega(\rho)} (r\rho)^{\frac{1}{2}} \Phi_\nu(r\rho) \phi_2\left(\frac{r\rho}{\nu}\right) \chi_1(r) F(r, t) dr dt. \end{aligned}$$

For the estimate  $S_\pm F$ , it suffices to consider  $S_+ F$ . We decompose it into two parts as follows:

$$S_+ F(\rho) = I + II$$

where

$$\begin{aligned} I &= \frac{c_{n,k} b_+}{(1 + \rho^2)^{\frac{s}{2}}} \int_{\mathbb{R}} \int_0^\infty e^{i(r\rho - t\Omega(\rho))} \chi_1(r) F(r, t) dr dt, \\ II &= \frac{c_{n,k} b_+}{(1 + \rho^2)^{\frac{s}{2}}} \int_{\mathbb{R}} \int_0^\infty e^{i(r\rho - t\Omega(\rho))} (1 - \phi\left(\frac{r\rho}{\nu}\right)) \chi_1(r) F(r, t) dr dt. \end{aligned}$$

For  $II$ , we have

$$\begin{aligned} |II| &\lesssim (1 + \rho^2)^{-\frac{s}{2}} \int_0^{\min(\frac{3\nu}{\rho}, 2)} \|F(r, \cdot)\|_{L^1} dr \\ &\lesssim (1 + \rho^2)^{-\frac{s}{2}} \left( \min\left(\frac{3\nu}{\rho}, 2\right) \right)^{\frac{1}{2}} \|F\|_{L^2 L^1} \end{aligned}$$

and hence

$$(2.10) \quad \|II\|_{L^2} \lesssim \nu^{\frac{1}{2}-s} \|F\|_{L^2 L^1}.$$

Now we estimate  $I$ . Since  $F$  is in  $C_0^\infty(\mathbb{R}_+ \times \mathbb{R})$ , obviously we may assume

$$I = \frac{c_n k b_+}{(1 + \rho^2)^{\frac{s}{2}}} \int_{\mathbb{R}^2} e^{i(r\rho - t\Omega(\rho))} \chi_1(|r|) F(r, t) dr dt.$$

Squaring and integrating  $I$  over  $\{|\rho| \leq N\}$ , we have

$$(2.11) \quad \int_{|\rho| < N} |I|^2 d\rho \leq C \|F\|_{L^2 L^1}^2.$$

Since  $\frac{1}{4} \leq s \leq \frac{1}{2}$ , it is easy to see

$$\begin{aligned} &\int_{|\rho| > N} |I|^2 d\rho \\ &\leq C \iiint |K(r - r', t - t')| \chi_1(|r|) |F(r, t)| \chi_1(|r'|) |F(r', t')| dr dr' dt dt', \end{aligned}$$

where

$$K(r, t) = \int_{|\rho| > N} e^{i(r\rho - t\Omega(\rho))} \frac{d\rho}{|\rho|^{\frac{1}{2}}}.$$

For the kernel estimate, we introduce a lemma which shows uniform bound of kernel  $K$  on  $t$ .

**Lemma 2.1.** *For any real number  $A, B (A \neq 0)$  and  $s \in [\frac{1}{2}, 1)$ , there exists a constant  $C$  independent of  $A$  and  $B$  such that*

$$\left| \int_{|\rho| > N} e^{i(A\Omega(\rho) + B\rho)} \frac{d\rho}{|\rho|^s} \right| \leq C |B|^{-(1-s)}.$$

Applying Lemma 2.1 with  $s = \frac{1}{2}$  and  $B = r - r'$ , from fractional integration it follows

$$\begin{aligned} &\int_{|\rho| > N} |I|^2 d\rho \\ (2.12) \quad &\lesssim \iint |r - r'|^{-\frac{1}{2}} \chi_1(|r|) \|F(r, \cdot)\|_{L^1} \chi_1(|r'|) \|F(r', \cdot)\|_{L^1} dr dr' \\ &\lesssim \|\mathcal{I}_{\frac{1}{2}}(\chi_1 \|F\|_{L^1})\|_{L^4} \|\chi_1 \|F\|_{L^1}\|_{L^{\frac{4}{3}}} \\ &\lesssim \|F\|_{L^2 L^1}^2, \end{aligned}$$

where  $\mathcal{I}_{\frac{1}{2}}$  is the Riesz potential of order  $\frac{1}{2}$ .

Finally, we estimate  $S_3F$ . From the uniform bound of  $\Phi_\nu$  on  $\nu$ , for small  $\varepsilon > 0$ , we have

$$\begin{aligned} |S_3F(\rho)| &\leq \frac{C}{(1+\rho^2)^{\frac{s}{2}}} \int (r\rho)^{-\frac{1}{2}} \phi_2\left(\frac{r\rho}{\nu}\right) \chi_1(r) \|F(r, \cdot)\|_{L^1} dr \\ &\leq C\rho^{-s-\frac{1}{2}} \chi_{\{\rho \geq \nu\}} \int_{\frac{2\nu}{\rho}}^2 r^{-\frac{1}{2}} \|F(r, \cdot)\|_{L^1} dr \\ &\leq C_\varepsilon \nu^{-\varepsilon} \rho^{-s-\frac{1}{2}+\varepsilon} \chi_{\{\rho \geq \nu\}} \int_{\frac{2\nu}{\rho}}^2 r^{-\frac{1}{2}+\varepsilon} \|F(r, \cdot)\|_{L^1} dr \\ &\leq C_\varepsilon \nu^{-\varepsilon} \rho^{-s-\frac{1}{2}+\varepsilon} \chi_{\{\rho \geq \nu\}} \|F\|_{L^2L^1}. \end{aligned}$$

Choosing  $\varepsilon$  as  $\frac{1}{8}$ , we obtain

$$(2.13) \quad \|S_3F\|_{L^2} \lesssim \nu^{-s} \|F\|_{L^2L^1}.$$

Combining all the estimates (2.8) to (2.13) and recalling  $\nu = \frac{2k+n-2}{2}$ , we get (2.4) and hence Theorem 1.2.

*Proof of Lemma 2.1.* To prove Lemma 2.1, we need the following (see e.g. [8] and [15])

**Lemma 2.2.** *Let  $\psi$  be a monotone function and  $I = \int_\alpha^\beta e^{i\varphi(\rho)} \psi(\rho) d\rho$ . Then if  $|\frac{d\varphi}{d\rho}| \geq \lambda > 0$  in  $[\alpha, \beta]$  and  $\frac{d\varphi}{d\rho}$  is monotone,  $|I| \leq C\lambda^{-1} \sup_{[\alpha, \beta]} |\psi(\rho)|$ , and if  $|\frac{d^2\varphi}{d\rho^2}| \geq \lambda > 0$ , then  $|I| \leq C\lambda^{-\frac{1}{2}} \sup_{[\alpha, \beta]} |\psi(\rho)|$ . The constant  $C$  doesn't depend on  $\alpha, \beta, \lambda, \varphi$  and  $\psi$ .*

We may assume that  $N = 0$  because there is no harm to the entire estimates. And by symmetry, we also assume that  $A > 0$  and  $B > 0$ .

(Case  $a > 1$ ) Let  $D = \frac{B}{A^{\frac{1}{a}}}$ . Then by the change of variable, we have

$$I = A^{-\frac{1-s}{a}} \int e^{i(A\Omega(A^{-\frac{1}{a}}\rho) + D\rho)} |\rho|^{-s} d\rho = \int_{\rho < 0} + \int_{\rho > 0} = I_- + I_+.$$

We have only to consider  $I_+$  and we denote it  $I$  again.

Now we first consider the case when  $\Omega' > 0$ . Observe that

$$E \equiv (A\Omega(A^{-\frac{1}{a}}\rho) + D\rho)' \geq c_1\rho^{a-1} + D.$$

Let  $M$  be a large positive number depending only on  $a, s, c_1, c_2$ . If  $D \leq M$ , then

$$I = A^{-\frac{1-s}{a}} \left( \int_0^1 + \int_1^\infty \right) = I_1 + I_2$$

For  $I_1$ , by direct integration, we have  $|I_1| \lesssim A^{-\frac{1-s}{a}} \lesssim B^{-(1-s)}$ . For  $I_2$ , since  $E \gtrsim 1$ , by the first part of (2.2), we have  $|I_2| \lesssim A^{-\frac{1-s}{a}} \lesssim B^{-(1-s)}$ . If  $D > M$ , then since



$E \geq D$ , by the first part of Lemma 2.2, we have  $|I_2| \lesssim A^{-\frac{1-s}{a}} D^{-1} \leq A^{\frac{s}{a}} B^{-1} \leq B^{-(1-s)}$ . For  $I_1$ , using the change of variable, we have

$$I_1 = A^{-\frac{1-s}{a}} D^{-(1-s)} \int_0^D e^{i(A\Omega(D^{-1}A^{-\frac{1}{a}}\rho)+\rho)} \rho^{-s} d\rho.$$

Thus  $I_1 = \int_0^1 + \int_1^D = I_{1,1} + I_{1,2}$ . By the integration,  $|I_{1,1}| \lesssim B^{-(1-s)}$ . For  $I_{1,2}$ , since  $(A\Omega(D^{-1}A^{-\frac{1}{a}}\rho) + \rho)' \geq 1$ , from the first part of Lemma 2.2, we have  $|I_{1,2}| \lesssim B^{-(1-s)}$  and hence  $|I_1| \lesssim B^{-(1-s)}$ .

Now we consider the case when  $\Omega' < 0$ . We observe that

$$-c_2\rho^{a-1} + D \leq E = (A\Omega(A^{-\frac{1}{a}}\rho) + D\rho)' \leq -c_1\rho^{a-1} + D.$$

If  $D \leq M$ , then we split  $I$  into two parts as follows:

$$I = A^{-\frac{1-s}{a}} \left( \int_0^{(\frac{2M}{c_2})^{\frac{1}{a-1}}} + \int_{(\frac{2M}{c_2})^{\frac{1}{a-1}}}^\infty \right) = I_3 + I_4.$$

For  $I_3$ , we have by direct integration  $|I_3| \lesssim A^{-\frac{1-s}{a}} \leq B^{-(1-s)}$ . For  $I_4$ , since  $E \leq -c_1\rho^{a-1} + D \leq -1$ , by the first part of Lemma 2.2, we get  $|I_4| \lesssim A^{-\frac{1-s}{a}} \leq B^{-(1-s)}$ .

If  $D > M$ , then we split  $I$  into four parts as follows:

$$(2.14) \quad I = A^{-\frac{1-s}{a}} \left( \int_0^1 + \int_1^{(\frac{D}{2c_2})^{\frac{1}{a-1}}} + \int_{(\frac{2D}{c_1})^{\frac{1}{a-1}}}^{(\frac{D}{2c_2})^{\frac{1}{a-1}}} + \int_{(\frac{2D}{c_1})^{\frac{1}{a-1}}}^\infty \right) \\ \equiv I_5 + I_6 + I_7 + I_8.$$

For  $I_5$ , we use the change of variable so that

$$I_5 = A^{-\frac{1-s}{a}} D^{-(1-s)} \int_0^D e^{i(A\Omega(D^{-1}A^{-\frac{1}{a}}\rho)+\rho)} \rho^{-s} d\rho.$$

We split  $I_5$  into two part:  $I_5 = A^{-\frac{1-s}{a}} D^{-(1-s)} \left( \int_0^1 + \int_1^D \right) = I_{5,1} + I_{5,2}$ . For  $I_{5,1}$  and  $I_{5,2}$ , using the direct integration and the first part of Lemma 2.2 respectively, we have  $|I_{5,1}| + |I_{5,2}| \lesssim A^{-\frac{1-s}{a}} D^{-(1-s)} = B^{-(1-s)}$ . For  $I_6$ , since  $E \gtrsim D \geq D^{1-s}$ , using the first part of Lemma 2.2, we have  $|I_6| \lesssim A^{-\frac{1-s}{a}} D^{-(1-s)} = B^{-(1-s)}$ .

To estimate  $I_7$ , we use the second derivative  $|E'| \sim \rho^{a-2} \sim D^{\frac{a-2}{a-1}}$ . Then from the second part of Lemma 2.2, we obtain

$$|I_7| \lesssim A^{-\frac{1-s}{a}} D^{-\frac{a-2}{2(a-1)}} D^{-\frac{s}{a-1}} = A^{-\frac{1-s}{a}} D^{-\frac{a-2+2s}{2(a-1)}}.$$

Since  $a > 1$  and  $s \geq \frac{1}{2}$ , we have  $|I_7| \lesssim A^{-\frac{1-s}{a}} D^{-(1-s)} = B^{-(1-s)}$ . Finally, we estimate  $I_8$ . Since  $E \gtrsim D \geq D^{1-s}$ , by the first part of Lemma 2.2, we have  $|I_8| \lesssim A^{-\frac{1-s}{a}} D^{-(1-s)} D^{-\frac{s}{a-1}} \lesssim B^{-(1-s)}$ .

**(Case  $a < 1$ )** Let  $\tilde{D} = \frac{A}{B^a}$ . Then by the change of variable, we write

$$B^{1-s} I = \int e^{i(A\Omega(\frac{\rho}{B})+\rho)} |\rho|^{-s} d\rho = \int_0^\infty + \int_{-\infty}^0 = I_+ + I_-.$$

Similarly to the case  $a > 1$ , we only consider  $I_+$  and denote it by  $I$  again.

In case that  $\Omega' > 0$ , we have  $E \equiv (A\Omega(\frac{\rho}{B}) + \rho)' \geq c_1 \tilde{D} \rho^{a-1} + 1 \geq 1$  for all  $\rho > 0$ . We divide  $I$  into two parts:  $I = \int_0^1 + \int_1^\infty$ . For the first integral, we just integrate and for the second one, we use the first part of Lemma 2.2. Then we can see  $|I| \lesssim 1$ .

Now we consider the case when  $\Omega' < 0$ . Then we can observe that

$$-c_2 \tilde{D} \rho^{a-1} + 1 \leq E \leq -c_1 \tilde{D} \rho^{a-1} + 1.$$

If  $c_2 \tilde{D} < 2$ , then we divide  $I$  into two parts:  $I = \int_0^{(\frac{1}{4})^{\frac{1}{a-1}}} + \int_{(\frac{1}{4})^{\frac{1}{a-1}}}^\infty = I_1 + I_2$ . By the integration, we get  $|I_1| \lesssim 1$ . And since  $c_2 \tilde{D} < 2$  and hence  $E \gtrsim 1$ , by the first part of Lemma 2.2, we have  $|I_2| \lesssim 1$ .

If  $c_1 \tilde{D} > 2$ , then we divide  $I$  into four parts:

$$I = \int_0^1 + \int_1^{(\frac{2}{c_1 \tilde{D}})^{\frac{1}{a-1}}} + \int_{(\frac{2}{c_1 \tilde{D}})^{\frac{1}{a-1}}}^{(\frac{1}{2c_2 \tilde{D}})^{\frac{1}{a-1}}} + \int_{(\frac{1}{2c_2 \tilde{D}})^{\frac{1}{a-1}}}^\infty = I_3 + I_4 + I_5 + I_6.$$

For  $I_3$ , by the integration,  $|I_3| \lesssim 1$ . For  $|I_5|$ , since  $|E'| \sim \tilde{D} \tilde{D}^{-\frac{a-2}{a-1}} = \tilde{D}^{\frac{1}{a-1}}$  and  $s \geq \frac{1}{2}$ , by the second part of Lemma 2.2, we have  $|I_5| \lesssim \tilde{D}^{\frac{2s-1}{2(a-1)}} \lesssim 1$ . And since  $E \lesssim -1$  on  $[1, (\frac{2}{c_1 \tilde{D}})^{\frac{1}{a-1}}]$  and  $E \gtrsim 1$  on  $[(\frac{1}{2c_2 \tilde{D}})^{\frac{1}{a-1}}, \infty)$ , we also have  $|I_4|, |I_6| \lesssim 1$ .

If  $\frac{2}{c_2} \leq \tilde{D} \leq \frac{2}{c_1}$ , choose a large number  $M$  depending only on  $c_1, c_2$ , and divide  $I$  as follows:  $I = \int_0^M + \int_M^\infty$ . Then as the estimate of  $I_1$  and  $I_2$ , we can obtain  $|I| \lesssim 1$ . This completes the proof of lemma.  $\square$

## REFERENCES

- [1] J. Bourgain, *A remark on Schrödinger operators*, Israel J. Math. **77** (1992), 1-16.
- [2] L. Carleson, *Some analytical problems related to statistical mechanics*, Euclidean Harmonic Analysis, Lecture Notes in Math. **779** (1979), 5-45.
- [3] Y. Cho and Y. Shim, *Weighted  $L^2$  estimates for maximal operators associated to dispersive equation*, to appear in Illinois J. Math..
- [4] Y. Cho and Y. Shim, *Global estimates of maximal operators generated by dispersive equations*, in preprint.
- [5] B. E. J. Dahlberg and C. E. Kenig, *A note on almost everywhere behavior of solutions to the Schrödinger equatin*, Harmonic Analysis, Lecture Notes in Math. **908** (1982), 205-209.
- [6] G. Gigante and F. Soria, *On the boundedness in  $H^{\frac{1}{4}}$  of the maximal square function associated with the Schrödinger equation*, in preprint.
- [7] H. P. Heinig and S. Wang, *Maximal function estimates of solutions to general dispersive partial differential equations*, Trans. Amer. Math. Soc. (1) **351** (1999), 79-108.
- [8] C. E. Kenig and A. Ruiz, *A strong type (2,2) estimate for a maximal operator associated to the Schrödinger equatin*, Trans. Amer. Math. Soc. **280** (1983), 239-246.
- [9] S. Machihara, M. Nakamura, K. Nakanishi and T. Ozawa, *Endpoint Strichartz estimates and global solutions for the nonlinear Dirac equation*, to appear in J. Func. Anal..
- [10] A. Moyua, A. Vargas and L. Vega, *Restriction theorems and Maximal operators related to oscillatory integrals in  $\mathbb{R}^3$* , Duke Math. J. (3) **96** (1999), 547-574.
- [11] P. Sjölin, *Global maximal estimates for solutions to the Schrödinger equation*, Studia. Math. (2) **110** (1994), 105-114.

- [12] P. Sjölin, *Radial functions and maximal estimates for solutions to the Schrödinger equation*, J. Austral. Math. Soc. (Series A) **59** (1995), 134-142.
- [13] P. Sjölin,  *$L^p$  Maximal estimates for solutions to the Schrödinger equation*, Math. Scand. **81** (1997), 35-68.
- [14] P. Sjölin, *A Counter-example Concerning Maximal Estimates for Solutions to Equations of Schrödinger Type*, Indiana Univ. Math. J. (2) **47** (1998), 593-599.
- [15] E. M. Stein, *Harmonic Analysis: Real-Variable Methods, Orthogonality, and Oscillatory Integrals*, Princeton Univ. Press, Princeton, N.J., (1993).
- [16] E. M. Stein and G. Weiss, *Introduction to Fourier Analysis on Euclidean Spaces*, Princeton Univ. Press, (1971).
- [17] K. Stempak, *A weighted uniform  $L^p$ - estimate of Bessel functions: a note on a paper of Guo*, Proc. Amer. Math. Soc. **128** (2000), 2943-2945.
- [18] T. Tao, *A sharp bilinear restriction estimate for paraboloids*, to appear in Geom. Funct. Anal.
- [19] L. Vega, *Schrödinger equations: pointwise convergence to the initial data*, Proc. Amer. Math. Soc. **102** (1988), 874-878.
- [20] B. G. Walther, *Homogeneous estimates for oscillatory integrals*, Acta Math. Univ. Comenianae, **9** (2000), 151-171.
- [21] B. G. Walther, *Higher integrability for maximal oscillatory Fourier integrals*, Annales Academiæ Scientiarum Fennicæ Mathematica **26** (2001), 189-204.
- [22] S. Wang, *On the maximal operator associated with the free Schrödinger equation*, Studia Math. **122** (1997), 167-182.
- [23] G. Watson, *A treatise on the theory of Bessel functions*, Reprint of the second (1944) edition. Cambridge Mathematical Library. Cambridge University Press, Cambridge, 1995.

YONGGEUN CHO:

DEPARTMENT OF MATHEMATICS, HOKKAIDO UNIVERSITY, SAPPORO 060-0810, JAPAN

*E-mail address:* ygcho@math.sci.hokudai.ac.jp

SANGHYUK LEE:

DEPARTMENT OF MATHEMATICS, UNIVERSITY OF WISCONSIN-MADISON, WI 53706-1388, USA

*E-mail address:* slee@math.wisc.edu

YONGSUN SHIM:

DEPARTMENT OF MATHEMATICS, POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY, POHANG 790-784, KOREA

*E-mail address:* shim@postech.ac.kr