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Small global solutions for the nonlinear Dirac equation

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1 Introduction

In this note we study the Cauchy problem for the nonlinear Dirac equation (*NLD*) in space-time \mathbb{R}^{1+n} :

$$\begin{aligned} \partial_t \psi &= (iA_0 + \sum_{j=1}^n A_j \partial_j) \psi + \lambda |(A_0 \psi | \psi)|^{(p-1)/2} \psi, \\ \psi(0) &= \phi, \end{aligned} \tag{1.1}$$

where $\psi : \mathbb{R}^{1+n} \rightarrow \mathbb{C}^{N(n)}$ is a function of $(t, x) \in \mathbb{R} \times \mathbb{R}^n$, $\phi : \mathbb{R}^n \rightarrow \mathbb{C}^{N(n)}$ is a given Cauchy data, $\lambda \in \mathbb{C}$ and $p > 1$ are constants, $\partial_t = \partial/\partial t$, $\partial_j = \partial/\partial x_j$ with space variable $x = (x_1, \dots, x_n)$, $(\cdot | \cdot)$ denotes the inner product in $\mathbb{C}^{N(n)}$. A_0, \dots, A_n denote the $N(n) \times N(n)$ matrices satisfying $A_i A_j + A_j A_i = 2\delta_{ij} I$, where δ_{ij} is Kronecker's delta and I is the unit matrix. $N(n)$ is an integer depending on the space dimension n .

There are several ways to construct the set of matrices satisfying the anticommutation relation above. The set of $(A_0^{(n)}, \dots, A_n^{(n)})$ for n dimensional case can be derived from $(A_0^{(n-1)}, \dots, A_{n-1}^{(n-1)})$ for $n-1$ dimensional case inductively.

Example 1 For $n = 1$, $A_0^{(1)} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, $A_1^{(1)} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$.

For $n \geq 2$, $A_j^{(n)} = \begin{pmatrix} 0 & A_j^{(n-1)} \\ A_j^{(n-1)} & 0 \end{pmatrix}$, $j = 0, \dots, n-1$, $A_n^{(n)} = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$.

Then $N(n) = 2^n$.

Example 2 For $n = 1$, $A_0^{(1)} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, $A_1^{(1)} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$. Let m be an integer.

For $n = 4m + 2$, $A_j^{(n)} = A_j^{(n-1)}$, $j = 0, \dots, n-1$, $A_n^{(n)} = iA_0^{(n-1)} \dots A_{n-1}^{(n-1)}$.

For $n = 4m + 1, 4m + 3$, $A_j^{(n)} = \begin{pmatrix} 0 & A_j^{(n-1)} \\ A_j^{(n-1)} & 0 \end{pmatrix}$, $j = 0, \dots, n-1$, $A_n^{(n)} = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$.

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For $n = 4m + 4$, $A_j^{(n)} = A_j^{(n-1)}$, $j = 0, \dots, n-1$, $A_n^{(n)} = A_0^{(n-1)} \dots A_{n-1}^{(n-1)}$.

Then $N(n) = 2^{\lfloor (n+1)/2 \rfloor}$, where $\lfloor a \rfloor$ denotes the largest integer which is less than or equal to a .

We consider the global existence of solution with small data for *NLD*. The case of $n = 3$ have been already studied in [3], [7]. Our basic tool for the proof is Strichartz estimate for Klein–Gordon equation which works for the space–time norm $L_t^q B_x$, $q \geq 2$, where B_x denotes suitable Besov spaces on \mathbb{R}^n . These estimates have been studied for $q > 2$, though the estimates for $q = 2$ i.e. $L_t^2 B_x$ have been excluded until lately and play an important role for our results. First study on the estimate for $q = 2$ was given by Lindblad and Sogge [6] and Ginibre and Velo [4] independently in 1995 for the wave equation. Keel and Tao [5] proved the end point estimate in 1998 for wave and Schrödinger equations. For Klein–Gordon equation, estimate on $q = 2$ can be found in [7]. In this note we give estimates applicable to more general norm in space variables.

Before stating our results, we shall give a scaling approach in this problem. For instance let us consider the massless case of *NLD*:

$$\partial_t \psi = \sum_{j=1}^n A_j \partial_j \psi + \lambda |(A_0 \psi | \psi)|^{(p-1)/2} \psi. \quad (1.2)$$

We scale the function ψ in the form

$$\psi_\gamma(t, x) = \gamma^{\frac{1}{p-1}} \psi(\gamma t, \gamma x), \quad \gamma > 0. \quad (1.3)$$

Then we see that ψ_γ is a solution of (1.2) if and only if ψ is a solution of (1.2). We take the initial data belonging to the homogeneous Sobolev space \dot{H}^s ,

$$\|\psi_\gamma(0)\|_{\dot{H}^s} = \gamma^{s-n/2+1/(p-1)} \|\psi(0)\|_{\dot{H}^s}. \quad (1.4)$$

Therefore we may think $s(p) := n/2 - 1/(p-1)$ as a critical exponent for *NLD*.

Now we give our results.

Theorem 3 *Let n, p, ϕ satisfy the following conditions:*

- (1) $n = 1$, $p \geq 5$, $\|\phi\|_{B_{2,1}^s} \ll 1$, $s = 1/2 + 1/(p-1)$,
- (2) $n = 2$, $3 < p \leq 5$, $\|\phi\|_{B_{2,1}^s} \ll 1$, $s = 1/2 + 1/(p-1)$,
- (3) $n = 2$, $p > 5$, $\|\phi\|_{H^{s(p)}} \ll 1$,
- (4) $n = 3$, $p = 3$, $\|\phi\|_{H^s} \ll 1$, $s > 1$,
- (5) $n = 3$, $p > 3$, $\|\phi\|_{H^{s(p)}} \ll 1$,
- (6) $n \geq 4$, $p = 3$, $\|\phi\|_{B_{2,1}^{s(3)}} \ll 1$,
- (7) $n \geq 4$, $p > 3$, $\|\phi\|_{H^{s(p)}} \ll 1$, $(s(p) < (p-1)/2$ if $p \neq \text{odd}$).

Then *NLD* has a solution $\psi \in C(\mathbb{R}; X)$, where X denotes the space of data indicated above.

Remark The cases (4), (5) were proved in [7], [3] respectively.

We close this section by introducing some notation. For any r with $1 \leq r \leq \infty$, $L^r = L^r(\mathbb{R}^n)$ denotes the Lebesgue space on \mathbb{R}^n . For any $s \in \mathbb{R}$ and any r with $1 < r < \infty$, H_r^s [resp. \dot{H}_r^s] denotes the inhomogeneous [resp. homogeneous] Sobolev space. For any $s \in \mathbb{R}$ and any r, m with $1 \leq r, m \leq \infty$, $B_{r,m}^s$ [resp. $\dot{B}_{r,m}^s$] denotes the inhomogeneous [resp. homogeneous] Besov space. We make abbreviations such as $H^s = H_2^s$, $\dot{H}^s = \dot{H}_2^s$, and $L_t^q B = L^q(\mathbb{R}; B)$. Occasionally we use \lesssim to mean $\leq C$, where C is a positive constant.

We give some properties for Sobolev and Besov spaces which seem to be important for following argument (see [1]).

$$H_p^\alpha \hookrightarrow H_q^\beta, \quad B_{p,m}^\alpha \hookrightarrow B_{q,m}^\beta \quad (1.5)$$

with $\alpha - n/p = \beta - n/q$, $\alpha \geq \beta$.

$$H_p^\alpha \hookrightarrow B_{p,2}^\alpha \quad [\text{resp. } B_{p,2}^\alpha \hookrightarrow H_p^\alpha] \quad (1.6)$$

with $p \leq 2$ [resp. $p \geq 2$].

$$B_{2,1}^\alpha \hookrightarrow B_{2,2}^\alpha = H^\alpha \hookrightarrow B_{2,1}^\beta \quad (1.7)$$

with $\alpha > \beta$. We often use the embedding

$$B_{\infty,1}^0 \hookrightarrow L^\infty. \quad (1.8)$$

2 Proof

We employ a contraction argument to obtain the solution. For this purpose, we prepare two lemmas, Strichartz estimate and interpolation estimate for L^∞ norm.

For simplicity we set $f(\psi) = \lambda |(A_0 \psi | \psi)|^{(p-1)/2} \psi$, and $\omega = (1 - \Delta)^{1/2}$. The solutions for *NLD* satisfy the following integral equation (see [7]):

$$\psi(t) = U(t)\phi + \int_0^t U(t-t')f(\psi(t'))dt' \quad (2.1)$$

with $U(t) := \cos t\omega + (iA_0 + \sum A_j \partial_j)\omega^{-1} \sin t\omega$. We investigate the operator $U(t)$. We give the following lemma which is often called Strichartz estimate.

Lemma 4 *Let $k = 1, 2$. The following estimate holds.*

$$\|U(t)u\|_{L^q(\mathbb{R}; B_{r,k}^{-\sigma})} \lesssim \|u\|_{B_{2,k}^0}, \quad (2.2)$$

where $0 \leq 1/q \leq 1/2$, $0 \leq 1/r \leq 1/2 - 2/(n-1+\theta)q$, $(n+\theta, q) \neq (3, 2)$ and

$$\frac{n}{2} - \frac{n-1-\theta}{n-1+\theta} \frac{1}{q} - \sigma - \frac{n}{r} = 0, \quad (2.3)$$

for $0 \leq \theta \leq 1$.

From (2.2), we have the homogeneous estimate as follows,

$$\begin{aligned} \left\| \int_0^t U(t-t')f(t')dt' \right\|_{L^q(\mathbb{R}; B_{r,k}^{-\sigma})} &\leq \int_{-\infty}^{\infty} \|U(t)U(-t')f(t')\|_{L^q(\mathbb{R}; B_{r,k}^{-\sigma})} dt' \\ &\lesssim \|f\|_{L^1(\mathbb{R}; B_{2,k}^0)}. \end{aligned} \quad (2.4)$$

Remark (i) The estimate for $k = 2$ was proved in [7]. (ii) We may replace $K(t) = e^{\pm it\omega}$ for $U(t)$. (iii) From the condition (2.3), if we take $\theta = 0$ and substitute the inhomogeneous norms by the homogeneous ones, i.e. $B_{r,k}^{-\sigma} \rightarrow \dot{B}_{r,k}^{-\sigma}$, $B_{2,k}^0 \rightarrow \dot{B}_{2,k}^0$, then the estimates (2.2) and (2.4) satisfy scaling invariance.

Proof of Lemma 4

We concentrate on the case $k = 1$. From duality argument, it is sufficient to prove that

$$\left\| \int_{-\infty}^{\infty} U(-t')F(t')dt' \right\|_{B_{2,\infty}^0} \lesssim \|F\|_{L_t^{q'} B_{r',\infty}^{\sigma}}, \quad (2.5)$$

where q' and r' denote the Hölder conjugate of q and r respectively. In fact in [7] we find

$$\left\| \int_{-\infty}^{\infty} U(-t')\varphi_k * F(t')dt' \right\|_{L^2} \lesssim 2^{k\sigma} \|\varphi_k * F\|_{L_t^{q'} L^{r'}}, \quad (2.6)$$

where $\{\varphi_k\}_0^\infty$ is the Littlewood–Paley dyadic decomposition on \mathbb{R}^n and q, r, σ are as in Lemma 4. We take supremum of k on both sides to obtain (2.5).

We use the following Gagliardo–Nirenberg type interpolation inequality ([3] or see [8] for more general cases).

Lemma 5 *The following estimate holds.*

$$\|f\|_{L^\infty} \lesssim \|f\|_{H_q^\alpha}^\delta \|f\|_{H_q^\beta}^{1-\delta}, \quad (2.7)$$

where $1 \leq p, q \leq \infty$, $0 < \alpha, \beta < \infty$, $0 < \delta < 1$, $\alpha > n/p$, $\beta < n/q$, $\delta(\alpha - n/p) + (1 - \delta)(\beta - n/q) = 0$.

Proof of Theorem 3

We define the complete metric space $\Phi = \Phi(p, s, k, M)$ for *NLD* as

$$\Phi = \{\psi \in L^\infty(\mathbb{R}; B_{2,k}^s) \cap L^{p-1}(\mathbb{R}; L^\infty); \|\psi\|_{L_t^\infty B_{2,k}^s} + \|\psi\|_{L_t^{p-1} L^\infty} \leq M\}. \quad (2.8)$$

We find a unique solution of *NLD* in Φ for sufficiently small data ψ and M . For any $s \in \mathbb{R}$, $k = 1, 2$ and q, r, σ satisfying the condition in Lemma 4, we have from (2.1), (2.2) and (2.4),

$$\begin{aligned} \|\psi\|_{L_t^q B_{r,k}^{s-\sigma}} &\lesssim \|\phi\|_{B_{2,k}^s} + \|f(\psi)\|_{L_t^1 B_{2,k}^s} \\ &\lesssim \|\phi\|_{B_{2,k}^s} + \|\psi\|_{L_t^{p-1} L^\infty}^{p-1} \|\psi\|_{L_t^\infty B_{2,k}^s}. \end{aligned} \quad (2.9)$$

So we concentrate on the $L_t^{p-1}L^\infty$ norm. We apply Lemma 4 to estimate it in $L_t^q B_{r,k}^{s-\sigma}$.

(1) $n = 1$. For any $p \geq 5$, we take $k = 1$ and

$$(s, q, r, \sigma, \theta) = (1/2 + 1/(p-1), p-1, \infty, 1/2 + 1/(p-1), 4/(p-1)) \quad (2.10)$$

and use $B_{\infty,1}^0 \hookrightarrow L^\infty$ to obtain the theorem.

(2) $n = 2$. For any $3 < p \leq 5$, we take $k = 1$ and

$$(s, q, r, \sigma, \theta) = (1/2 + 1/(p-1), p-1, \infty, 1/2 + 1/(p-1), (5-p)/(p-1)) \quad (2.11)$$

and use $B_{\infty,1}^0 \hookrightarrow L^\infty$ to obtain the theorem.

(3) $n = 2$. For any $p > 5$, we take $k = 2$ and $0 < \delta < 1$ satisfying $(1-\delta)(p-1) \geq 4$. From (2.7), we estimate

$$\|\psi\|_{L_t^{p-1}L^\infty} \lesssim \|\psi\|_{L_t^\infty H^s}^\delta \|\psi\|_{L_t^{(1-\delta)(p-1)} H^{s-\sigma}}^{1-\delta}. \quad (2.12)$$

We take

$$(s, q, r, \sigma, \theta) = (1-1/(p-1), (1-\delta)(p-1), 1/2-2/(1-\delta)(p-1), 3/(1-\delta)(p-1), 0) \quad (2.13)$$

to obtain the theorem.

(6) $n \geq 4$, $p = 3$. We take $k = 1$ and

$$(s, q, r, \sigma, \theta) = ((n-1)/2, 2, 2(n-1)/(n-3), (n+1)/2(n-1), 0) \quad (2.14)$$

and use $B_{r,1}^{s-\sigma} \hookrightarrow L^\infty$ to obtain the theorem.

(7) $n \geq 4$. For any $p > 3$, we take $k = 2$ and $0 < \delta < 1$ satisfying $(1-\delta)(p-1) \geq 2$. From (2.7), we estimate (2.12) and take

$$(s, q, r, \sigma, \theta) = (n/2 - 1/(p-1), (1-\delta)(p-1), (1/2-2/(1-\delta)(p-1)(n-1))^{-1}, \\ (n+1)/(1-\delta)(p-1)(n-1), 0)$$

to obtain the theorem.

3 Application for nonlinear Klein–Gordon equations

We apply the previous argument for the Klein–Gordon equation with derivative coupling (*NLKG*):

$$\partial_t^2 u - \Delta u + m^2 u = \lambda f(u), \quad u(0) = u_0, \quad \partial_t u(0) = u_1, \quad (3.1)$$

where $u : \mathbb{R}^{1+n} \rightarrow \mathbb{C}$ is unknown, $u_0, u_1 : \mathbb{R}^n \rightarrow \mathbb{C}$ are given Cauchy data, $m > 0$ and $\lambda \in \mathbb{C}$ are constants. We consider the nonlinear term $f(u)$ of following types:

$$f(u) = \partial_j(u^p), \partial_t(u^p), \prod_{j=1}^n (\partial_j u)^{p_j}, (\partial_t u)^{p_0} \prod_{j=1}^n (\partial_j u)^{p_j}, \quad (3.2)$$

where $1 \leq j \leq n$.

We give the results only. For simplicity we set $\varphi = (u_0, u_1)$ and $\|\varphi\|_{B_{2,k}^s} := \|u_0\|_{B_{2,k}^s} + \|u_1\|_{B_{2,k}^{s-1}}$.

Theorem 6 *Let n, p, ϕ satisfy the following conditions:*

- (1) $n = 1, \quad p \geq 5, \quad \|\varphi\|_{B_{2,1}^s} \ll 1, \quad s = 1/2 + 1/(p-1),$
- (2) $n = 2, \quad 3 < p \leq 5, \quad \|\varphi\|_{B_{2,1}^s} \ll 1, \quad s = 1/2 + 1/(p-1),$
- (3) $n = 2, \quad p > 5, \quad \|\varphi\|_{H^{s(p)}} \ll 1,$
- (4) $n = 3, \quad p = 3, \quad \|\varphi\|_{H^s} \ll 1, \quad s > 1,$
- (5) $n = 3, \quad p > 3, \quad \|\varphi\|_{H^{s(p)}} \ll 1,$
- (6) $n \geq 4, \quad p = 3, \quad \|\varphi\|_{B_{2,1}^{s(3)}} \ll 1,$
- (7) $n \geq 4, \quad p > 3, \quad \|\varphi\|_{H^{s(p)}} \ll 1, \quad (s(p) < p \text{ if } p \neq \text{integer}),$

(1) – (7) for $f = \partial_j(u^p)$, (4) – (7) for $f = \partial_t(u^p)$.

Then NLKG has a solution $\psi \in C(\mathbb{R}; X)$, where X denotes the space of data φ indicated above.

Remark In this case $s(p)$ is scaling critical exponent for massless NLKG ($m = 0$).

Theorem 7 *Let n, p, ϕ satisfy the following conditions:*

- (1) $n = 1, \quad p \geq 5, \quad \|\varphi\|_{B_{2,1}^{s+1}} \ll 1, \quad s = 1/2 + 1/(p-1),$
- (2) $n = 2, \quad 3 < p \leq 5, \quad \|\varphi\|_{B_{2,1}^{s+1}} \ll 1, \quad s = 1/2 + 1/(p-1),$
- (3) $n = 2, \quad p > 5, \quad \|\varphi\|_{H^{s(p)+1}} \ll 1,$
- (4) $n = 3, \quad p = 3, \quad \|\varphi\|_{H^{s+1}} \ll 1, \quad s > 1,$
- (5) $n = 3, \quad p > 3, \quad \|\varphi\|_{H^{s(p)+1}} \ll 1,$
- (6) $n \geq 4, \quad p = 3, \quad \|\varphi\|_{B_{2,1}^{s(3)+1}} \ll 1,$
- (7) $n \geq 4, \quad p > 3, \quad \|\varphi\|_{H^{s(p)+1}} \ll 1,$

(1) – (7) for $f = \prod_{j=1}^n (\partial_j u)^{p_j}$, $p_1 + \dots + p_n = p$, $p_j \in \mathbb{Z}^+ \cup \{0\}$ or $p_j > \max\{1, s\}$,

(4) – (7) for $f = (\partial_t u)^{p_0} \prod_{j=1}^n (\partial_j u)^{p_j}$, $p_0 + \dots + p_n = p$, $p_j \in \mathbb{Z}^+ \cup \{0\}$ or $p_j > \max\{1, s\}$.

Then NLKG has a solution $\psi \in C(\mathbb{R}; X)$, where X denotes the space of data φ indicated above.

Remark In this case $s(p)+1$ is scaling critical exponent for massless NLKG ($m = 0$).

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