

On inverse scattering for the multidimensional relativistic Newton equation at high energies

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Consider the Newton equation in the relativistic case (that is the Newton-Einstein equation) $\dot{p}=F(x)$, $F(x)=-\nabla V(x)$, $p=\dot{x}/\sqrt{1-(|\dot{x}|^2/c^2)}$, $p=dp/dt$, $\dot{x}=dx/dt$, $x \in C^1(\mathbb{R}, \mathbb{R}^d)$, where $V \in C^2(\mathbb{R}^d, \mathbb{R})$, $|\partial_x^j V(x)| \leq \beta_{|j|}(1+|x|)^{-(\alpha+|j|)}$ for $|j| \leq 2$ and some $\alpha > 1$. We give estimates and asymptotics for scattering solutions and scattering data for the equation for the case of small angle scattering. We show that at high energies the velocity valued component of the scattering operator uniquely determines the x-ray transform PF . Applying results on inversion of the x-ray transform P we obtain that for $d \geq 2$ the velocity valued component of the scattering operator at high energies uniquely determines F . In addition we show that our high energy asymptotics found for the configuration valued component of the scattering operator does not uniquely determine F . The results of the present work were obtained in the process of generalizing some results of Novikov to the relativistic case. © 2006 American Institute of Physics. [DOI: 10.1063/1.2206690]

I. INTRODUCTION

Consider the Newton equation in the relativistic case (that is the Newton-Einstein equation)

$$\dot{p} = F(x), \quad F(x) = -\nabla V(x),$$

$$p = \frac{\dot{x}}{\sqrt{1 - \frac{|\dot{x}|^2}{c^2}}}, \quad \dot{p} = \frac{dp}{dt}, \quad \dot{x} = \frac{dx}{dt}, \quad x \in C^1(\mathbb{R}, \mathbb{R}^d), \quad (1.1)$$

where

$$V \in C^2(\mathbb{R}^d, \mathbb{R}), \quad |\partial_x^j V(x)| \leq \beta_{|j|}(1+|x|)^{-(\alpha+|j|)} \quad (1.2)$$

for $|j| \leq 2$ and some $\alpha > 1$ [here j is the multi-index $j \in (\mathbb{N} \cup \{0\})^d$, $|j| = \sum_{n=1}^d j_n$ and $\beta_{|j|}$ are positive real constants]. The equation (1.1) is an equation for $x=x(t)$ and is the equation of motion in \mathbb{R}^d of a relativistic particle of mass $m=1$ and charge $e=1$ in an external electric field described by the scalar potential V (see Ref. 1 and, for example, Sec. 17 of Ref. 5). In this equation x is the position of the particle, p is its impulse, F is the force acting on the particle, t is the time and c is the speed of light.

For the equation (1.1) the energy

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$$E = c^2 \sqrt{1 + \frac{|p(t)|^2}{c^2}} + V(x(t))$$

is an integral of motion. We denote by B_c the Euclidean open ball whose radius is c and whose center is 0.

Yajima¹⁰ studied in dimension 3 (without loss of generality for the case of dimension $d \geq 2$) the direct scattering of relativistic particle in an external electromagnetic field described by four vector $(V(x), \mathbf{A}(x))$ where the scalar potential V and the vector potential \mathbf{A} are both rapidly decreasing. We recall the results of Yajima¹⁰ in our case.

Under the conditions (1.2), the following is valid (see Ref. 10): for any $(v_-, x_-) \in B_c \times \mathbb{R}^d$, $v_- \neq 0$, the equation (1.1) has a unique solution $x \in C^2(\mathbb{R}, \mathbb{R}^d)$ such that

$$x(t) = v_- t + x_- + y_-(t), \tag{1.3}$$

where $\dot{y}_-(t) \rightarrow 0$, $y_-(t) \rightarrow 0$, as $t \rightarrow -\infty$; in addition for almost any $(v_-, x_-) \in B_c \times \mathbb{R}^d$, $v_- \neq 0$,

$$x(t) = v_+ t + x_+ + y_+(t), \tag{1.4}$$

where $v_+ \neq 0$, $|v_+| < c$, $v_+ = a(v_-, x_-)$, $x_+ = b(v_-, x_-)$, $\dot{y}_+(t) \rightarrow 0$, $y_+(t) \rightarrow 0$, as $t \rightarrow +\infty$.

The map $S: B_c \times \mathbb{R}^d \rightarrow B_c \times \mathbb{R}^d$ given by the formulas

$$v_+ = a(v_-, x_-), \quad x_+ = b(v_-, x_-) \tag{1.5}$$

is called the scattering map for the equation (1.1); in addition, $a(v_-, x_-)$, $b(v_-, x_-)$ are called the scattering data for the equation (1.1).

By $\mathcal{D}(S)$ we denote the domain of definition of S ; by $\mathcal{R}(S)$ we denote the range of S [by definition, if $(v_-, x_-) \in \mathcal{D}(S)$, then $v_- \neq 0$ and $a(v_-, x_-) \neq 0$].

Under the conditions (1.2), the map S has the following simple properties (see Ref. 10): for any $(v, x) \in B_c \times \mathbb{R}^d$, $(v, x) \in \mathcal{D}(S)$ if and only if $(-v, x) \in \mathcal{R}(S)$; $\mathcal{D}(S)$ is an open set of $B_c \times \mathbb{R}^d$ and $\text{Mes}((B_c \times \mathbb{R}^d) \setminus \mathcal{D}(S)) = 0$ for the Lebesgue measure on $B_c \times \mathbb{R}^d$ induced by the Lebesgue measure on $\mathbb{R}^d \times \mathbb{R}^d$; the map $S: \mathcal{D}(S) \rightarrow \mathcal{R}(S)$ is continuous and preserves the element of volume, $a(v_-, x_-)^2 = v_-^2$.

If $V(x) \equiv 0$, then $a(v_-, x_-) = v_-$, $b(v_-, x_-) = x_-$, $(v_-, x_-) \in B_c \times \mathbb{R}^d$, $v_- \neq 0$. Therefore for $a(v_-, x_-)$, $b(v_-, x_-)$ we will use the following representation:

$$\begin{aligned} a(v_-, x_-) &= v_- + a_{sc}(v_-, x_-) \\ b(v_-, x_-) &= x_- + b_{sc}(v_-, x_-) \end{aligned} \quad (v_-, x_-) \in \mathcal{D}(S). \tag{1.6}$$

We will use the fact that, under the conditions (1.2), the map S is uniquely determined by its restriction to $\mathcal{M}(S) = \mathcal{D}(S) \cap \mathcal{M}$, where

$$\mathcal{M} = \{(v_-, x_-) \in B_c \times \mathbb{R}^d \mid v_- \neq 0, v_- x_- = 0\}.$$

Consider

$$TS^{d-1} = \{(\theta, x) \mid \theta \in S^{d-1}, \quad x \in \mathbb{R}^d, \theta x = 0\},$$

where S^{d-1} is the unit sphere in \mathbb{R}^d .

Consider the x-ray transform P which maps each function f with the properties

$$f \in C(\mathbb{R}^d, \mathbb{R}^m), \quad |f(x)| = O(|x|^{-\beta}), \quad \text{as } |x| \rightarrow \infty, \quad \text{for some } \beta > 1$$

into a function $Pf \in C(TS^{d-1}, \mathbb{R}^m)$, where Pf is defined by

$$Pf(\theta, x) = \int_{-\infty}^{+\infty} f(t\theta + x) dt, \quad (\theta, x) \in TS^{d-1}.$$

Concerning the theory of the x-ray transform, the reader is referred to Refs. 8, 2, 6, and 7.

Let

$$\mu(c, d, \tilde{\beta}, \alpha, r_v, r_x, r) = \frac{1}{\sqrt{1 + \frac{r_v^2}{4(c^2 - r_v^2)}}} \frac{2^{2\alpha+6}(1 + 3\tilde{\beta}/c)d^2\sqrt{d}\tilde{\beta}(r_v/\sqrt{2} + 1 - r)^3}{r(\alpha - 1)(r_v/\sqrt{2} - r)^4(1 + r_x/\sqrt{2})^{\alpha-1}} \quad (1.7a)$$

and let $z = z(c, d, \tilde{\beta}, \alpha, r_x, r)$, $z_1 = z_1(c, d, \beta_1, \alpha, r_x, r)$, and $z_2 = z_2(c, d, \beta_1, \alpha, r_x)$ be defined as the roots of the following equations:

$$\mu(c, d, \tilde{\beta}, \alpha, z, r_x, r) = 1, \quad z \in]\sqrt{2}r, c[, \quad (1.7b)$$

$$\frac{z_1}{\sqrt{1 - \frac{z_1^2}{c^2}}} - \frac{2^{\alpha+4}\beta_1\sqrt{d}}{\alpha(z_1/\sqrt{2} - r)(r_x/\sqrt{2} + 1)^\alpha} = 0, \quad z_1 \in]\sqrt{2}r, c[, \quad (1.7c)$$

$$\frac{z_2}{\sqrt{1 - \frac{z_2^2}{c^2}}} - \frac{8\beta_1\sqrt{d}}{\alpha(z_2/\sqrt{2})(1 + r_x/\sqrt{2})^\alpha} = 0, \quad z_2 \in]0, c[, \quad (1.7d)$$

where r_v , r_x , and r are some non-negative numbers such that $0 < r \leq 1$, $r < c/\sqrt{2}$, $\sqrt{2}r < r_v < c$, and where $\tilde{\beta} = \max(\beta_1, \beta_2)$.

The main results of the present work consist in the small angle scattering asymptotics and estimates for the scattering data a_{sc} and b_{sc} (and scattering solutions) for the equation (1.1) and in application of these asymptotics and estimates to inverse scattering for the equation (1.1) at high energies. Our main results include, in particular, Theorem 1.1 and Proposition 1.1 given below.

Theorem 1.1: *Let the conditions (1.2) be valid, $\tilde{\beta} = \max(\beta_1, \beta_2)$, $(\theta, x) \in TS^{d-1}$, and let r be a positive constant such that $0 < r \leq 1$, $r < c/\sqrt{2}$. Then*

$$PF(\theta, x) = \lim_{\substack{s \rightarrow c \\ s < c}} \frac{s}{\sqrt{1 - \frac{s^2}{c^2}}} a_{sc}(s\theta, x), \quad (1.8a)$$

and, in addition,

$$\left| PF(\theta, x) - \frac{s}{\sqrt{1 - \frac{s^2}{c^2}}} a_{sc}(s\theta, x) \right| \leq \frac{d^2 \tilde{\beta}^2 2^{2\alpha+5} s (s/\sqrt{2} + 1 - r)^2}{\sqrt{1 + \frac{s^2}{4(c^2 - s^2)}} \alpha(\alpha - 1)(s/\sqrt{2} - r)^4 (1 + |x|/\sqrt{2})^{2\alpha-1}} \quad (1.8b)$$

for $s < c$, $s > z(c, d, \tilde{\beta}, \alpha, |x|, r)$, $s \geq z_1(c, d, \beta_1, \alpha, |x|, r)$;

$$\int_{-\infty}^0 \int_{-\infty}^{\tau} F(s\theta + x) ds d\tau - \int_0^{+\infty} \int_{\tau}^{+\infty} F(s\theta + x) ds d\tau + PV(\theta, x)\theta = \lim_{\substack{s \rightarrow c \\ s < c}} \frac{s^2}{\sqrt{1 - \frac{s^2}{c^2}}} b_{sc}(s\theta, x) \quad (1.9a)$$

and, in addition,

$$\left| \frac{b_{sc}(s\theta, x)}{\sqrt{1 - \frac{s^2}{c^2}}} - \frac{1}{c^2} PV(\theta, x)\theta + \frac{1}{s^2} \int_0^{+\infty} \int_{-\tau}^{+\infty} F(u\theta + x) du d\tau - \frac{1}{s^2} \int_{-\infty}^0 \int_{-\infty}^{-\tau} F(u\theta + x) du d\tau \right|$$

$$\leq \sqrt{1 - \frac{s^2}{c^2}} \left[C + \frac{d^3 \sqrt{d} \left(\beta_2 + 3 \frac{\beta_1 \beta_2}{c} \right) \beta_1 2^{3\alpha+8} \left(\frac{s}{\sqrt{2}} + 1 - r \right)^3}{\left(1 - \frac{3s^2}{4c^2} \right) \alpha(\alpha-1)^2 \left(\frac{s}{\sqrt{2}} - r \right)^6 \left(1 + \frac{|x|}{\sqrt{2}} \right)^{2\alpha-2}} \right] \quad (1.9b)$$

for $s < c$, $s > z(c, d, \tilde{\beta}, \alpha, |x|, r)$, $s \geq \max(z_1(c, d, \beta_1, \alpha, |x|, r), z_2(c, d, \beta_1, \alpha, |x|))$ and some constant $C = C(c, d, \beta_0, \beta_1, \alpha, |x|)$ which can be given explicitly.

Consider the vector function w of (θ, x) arising on the left-hand side of (1.9a),

$$w(V, \theta, x) = \int_{-\infty}^0 \int_{-\infty}^{-\tau} F(s\theta + x) ds d\tau - \int_0^{+\infty} \int_{-\tau}^{+\infty} F(s\theta + x) ds d\tau + PV(\theta, x)\theta, \quad (\theta, x) \in \mathbb{TS}^{d-1}.$$

Proposition 1.1: The vector w as a function of potential V satisfying the conditions (1.2) and of $(\theta, x) \in \mathbb{TS}^{d-1}$ has the following simple properties:

- (1) under the conditions (1.2), for any potential V the vector $w(V, \theta, x)$ is orthogonal to θ ,
- (2) there exists a potential V which satisfies the conditions (1.2) and for which $w(V, \theta, x)$ is not null for all $(\theta, x) \in \mathbb{TS}^{d-1}$,
- (3) for any spherical symmetric potential V satisfying the conditions (1.2) we have $w(V, \theta, x) = 0$ for all $(\theta, x) \in \mathbb{TS}^{d-1}$.

From (1.8a) and inversion formulas for the x-ray transform for $d \geq 2$ (see Refs. 8, 2, 6, and 7) it follows that a_{sc} determines uniquely F at high energies. Moreover for $d \geq 2$ methods of reconstruction of f from Pf (see Refs. 8, 2, 6, and 7) permit to reconstruct F from the velocity valued component a of the scattering map at high energies. The formula (1.9a) and the item (3) of Proposition 1.1 show that the first term of the asymptotics of b_{sc} does not uniquely determine the potential V or the force F . The item (2) of Proposition 1.1 ensures us that the asymptotics which was found for b_{sc} is nontrivial. Note that Nicoleau paid our attention to the fact that, in addition of the item (3) of Proposition 1.1, $w(V, \theta, x)$, $(\theta, x) \in \mathbb{TS}^{d-1}$, uniquely determines V satisfying (1.2) modulo spherical symmetric potentials.

Inverse scattering for the classical multidimensional Newton equation was first studied by Novikov⁷ (the existence of the scattering states, asymptotic completeness and scattering map for the classical Newton equation was studied by Simon⁹). Novikov proved two formulas which link scattering data at high energies to the x-ray transform of F and V . These formulas are generalized to the relativistic case by the formulas (1.8a) and (1.9a) of Theorem 1.1. Then applying results on inversion of the x-ray transform, Novikov obtains that at high energies the velocity valued component of the scattering data determines uniquely the x-ray transform of F whereas the configuration valued component of the scattering operator determines uniquely the x-ray transform of V . Note that in the relativistic case [due to the formula (1.9a) and Proposition 1.1] the asymptotics of b_{sc} does not determine uniquely F . We follow Novikov's framework⁷ to obtain our results. Note also that for the classical multidimensional Newton equation in a bounded open strictly convex domain an inverse boundary value problem at high energies was first studied in Ref. 3.

Further our paper is organized as follows. In Sec. II we transform the differential equation (1.1) with initial conditions (1.3) in an integral equation which takes the form $y_- = A_{v_-, x_-}(y_-)$. Then we study A_{v_-, x_-} on a suitable space and we give estimates and contraction estimates about A_{v_-, x_-} (Lemmas 2.1, 2.2, 2.3). In Sec. III we give estimates and asymptotics for the deflection $y_-(t)$ from (1.3) and for scattering data $a_{sc}(v_-, x_-)$, $b_{sc}(v_-, x_-)$ from (1.6) (Theorem 3.1 and Theorem 3.2). From these estimates and asymptotics the formulas (1.8a) and (1.9a) will follow when the parameters c , β_m , α , d , \hat{v}_- , x_- are fixed and $|v_-|$ increases [where $\beta_{|j|}$, α , d are constants from (1.2),

$\beta_m = \max(\beta_0, \beta_1, \beta_2)$; $\hat{v}_- = v_- / |v_-|$. In these cases $\sup_{t \in \mathbb{R}} |\theta(t)|$ decreases, where $\theta(t)$ denotes the angle between the vectors $\dot{x}(t) = v_- + \dot{y}_-(t)$ and v_- , and we deal with small angle scattering. Note that, under the conditions of Theorem 3.1, without additional assumptions, there is the estimate $\sup_{t \in \mathbb{R}} |\theta(t)| < \frac{1}{4}\pi$ and we deal with rather small angle scattering (concerning the term ‘‘small angle scattering’’ see Ref. 7 and Sec. 20 of Ref. 4). Theorem 1.1 follows from Theorem 3.1 and Theorem 3.2. Section IV, Sec. V, and Sec. VI are devoted to Proofs of our Theorems and Lemmas.

II. A CONTRACTION MAP

Let us transform the differential equation (1.1) in an integral equation. Consider the function $g: \mathbb{R}^d \rightarrow B_c$ defined by

$$g(x) = \frac{x}{\sqrt{1 + \frac{|x|^2}{c^2}}},$$

where $x \in \mathbb{R}^d$. One can see that g has, in particular, the following simple properties:

$$|g(x) - g(y)| \leq \sqrt{d}|x - y| \quad \text{for } x, y \in \mathbb{R}^d, \quad (2.1)$$

g is an infinitely smooth diffeomorphism between \mathbb{R}^d and B_c , and its inverse is given by

$$\gamma(x) = \frac{x}{\sqrt{1 - \frac{|x|^2}{c^2}}}, \quad x \in B_c.$$

Now, if x satisfies the differential equation (1.1) and the initial conditions (1.3), then x satisfies the integral equation

$$x(t) = v_- t + x_- + \int_{-\infty}^t \left[g \left(\gamma(v_-) + \int_{-\infty}^{\tau} F(x(s)) ds \right) - v_- \right] d\tau, \quad (2.2)$$

where $F(x) = -\nabla V(x)$, $v_- \in B_c \setminus \{0\}$.

For $y_-(t)$ this equation takes the form

$$y_-(t) = A_{v_-, x_-}(y_-(t)), \quad (2.3)$$

where

$$A_{v_-, x_-}(f)(t) = \int_{-\infty}^t \left[g \left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_- s + x_- + f(s)) ds \right) - v_- \right] d\tau, \quad v_- \in B_c \setminus \{0\}.$$

From (2.2), (1.2), and (2.1) [applied on ‘‘ x ’’ = $\gamma(v_-) + \int_{-\infty}^{\tau} F(x(s)) ds$ and ‘‘ y ’’ = $\gamma(v_-)$], and $y_-(t) \in C(\mathbb{R}, \mathbb{R}^d)$, $y_-(t) \rightarrow 0$, as $t \rightarrow -\infty$, it follows, in particular, that

$$y_-(t) \in C^1(\mathbb{R}, \mathbb{R}^d) \quad \text{and} \quad |\dot{y}_-(t)| = O(|t|^{-\alpha}), \quad |y_-(t)| = O(|t|^{-\alpha+1}), \quad \text{as } t \rightarrow -\infty, \quad (2.4)$$

where $v_- \in B_c \setminus \{0\}$ and x_- are fixed.

Consider the complete metric space

$$M_{T, r} = \{f \in C^1([-\infty, T], \mathbb{R}^d) \mid \|f\|_T \leq r\},$$

where

$$\|f\|_T = \max\left(\sup_{t \in]-\infty, T]} |\dot{f}(t)|, \sup_{t \in]-\infty, T]} |f(t) - t\dot{f}(t)|\right) \tag{2.5}$$

(where for $T = +\infty$ we understand $]-\infty, T]$ as $]-\infty, +\infty[$). From (2.4) it follows that, at fixed $T < +\infty$,

$$y_-(t) \in M_{T,r} \text{ for some } r \text{ depending on } y_-(t) \text{ and } T. \tag{2.6}$$

Lemma 2.1: Under the conditions (1.2), the following is valid: if $f \in M_{T,r}$, $0 < r \leq 1$, $r < c/\sqrt{2}$, $|v_-| < c$, $|v_-| \geq z_1(c, d, \beta_1, \alpha, |x_-|, r)$, $v_{-x_-} = 0$, then

$$\begin{aligned} \|A_{v_{-x_-}}(f)\|_T &\leq \rho_T(c, d, \beta_1, \alpha, |v_-|, |x_-|, r) \\ &= \frac{1}{\sqrt{1 + |v_-|^2/(4(c^2 - |v_-|^2))}} \frac{2^{\alpha+1} d \beta_1 (|v_-|/\sqrt{2} + 1 - r)}{(\alpha - 1)(|v_-|/\sqrt{2} - r)^2 (1 + |x_-|/\sqrt{2} - (|v_-|/\sqrt{2} - r)T)^{\alpha-1}} \end{aligned} \tag{2.7a}$$

for $T \leq 0$,

$$\begin{aligned} \|A_{v_{-x_-}}(f)\|_T &\leq \rho(c, d, \beta_1, \alpha, |v_-|, |x_-|, r) \\ &= \frac{1}{\sqrt{1 + |v_-|^2/(4(c^2 - |v_-|^2))}} \frac{2^{\alpha+2} d \beta_1 (|v_-|/\sqrt{2} + 1 - r)}{(\alpha - 1)(|v_-|/\sqrt{2} - r)^2 (1 + |x_-|/\sqrt{2})^{\alpha-1}} \end{aligned} \tag{2.7b}$$

for $T \leq +\infty$; if $f_1, f_2 \in M_{T,r}$, $0 < r \leq 1$, $r < c/\sqrt{2}$, $|v_-| < c$, $|v_-| \geq z_1(c, d, \beta_1, \alpha, |x_-|, r)$, $v_{-x_-} = 0$, then

$$\|A_{v_{-x_-}}(f_2) - A_{v_{-x_-}}(f_1)\|_T \leq \lambda_T(c, d, \beta_2, \alpha, |v_-|, |x_-|, r) \|f_2 - f_1\|_T,$$

$$\begin{aligned} \lambda_T(c, d, \beta_2, \alpha, |v_-|, |x_-|, r) &= \frac{1}{\sqrt{1 + |v_-|^2/(4(c^2 - |v_-|^2))}(\alpha - 1)} \\ &\times \frac{2^{\alpha+2} d \sqrt{d} \beta_2 (|v_-|/\sqrt{2} + 1 - r)^2}{(|v_-|/\sqrt{2} - r)^3 (1 + |x_-|/\sqrt{2} - (|v_-|/\sqrt{2} - r)T)^{\alpha-1}} \end{aligned} \tag{2.8a}$$

for $T \leq 0$,

$$\|A_{v_{-x_-}}(f_2) - A_{v_{-x_-}}(f_1)\|_T \leq \lambda(c, d, \beta_1, \beta_2, \alpha, |v_-|, |x_-|, r) \|f_2 - f_1\|_T,$$

$$\lambda(c, d, \beta_1, \beta_2, \alpha, |v_-|, |x_-|, r) = \frac{1}{\sqrt{1 + |v_-|^2/(4(c^2 - |v_-|^2))}} \frac{2^{2\alpha+6} (\beta_2 + 3\beta_1\beta_2/c) d^2 \sqrt{d} (|v_-|/\sqrt{2} + 1 - r)^3}{(\alpha - 1)(|v_-|/\sqrt{2} - r)^4 (1 + |x_-|/\sqrt{2})^{\alpha-1}} \tag{2.8b}$$

for $T \leq +\infty$.

Note that

$$\begin{aligned} \max\left(\frac{\rho_T(c, d, \beta_1, \alpha, |v_-|, |x_-|, r)}{r}, \lambda_T(c, d, \beta_2, \alpha, |v_-|, |x_-|, r)\right) &\leq \mu_T(c, d, \tilde{\beta}, \alpha, |v_-|, |x_-|, r) \\ &= \frac{1}{\sqrt{1 + |v_-|^2/(4(c^2 - |v_-|^2))}} \frac{2^{\alpha+2} d \sqrt{d} \tilde{\beta} (|v_-|/\sqrt{2} + 1 - r)^2}{r(\alpha - 1)(|v_-|/\sqrt{2} - r)^3 (1 + |x_-|/\sqrt{2} - (|v_-|/\sqrt{2} - r)T)^{\alpha-1}} \end{aligned} \tag{2.9a}$$

for $T \leq 0$,

$$\begin{aligned} & \max\left(\frac{\rho(c,d,\beta_1,\alpha,|v_-|,|x_-|,r)}{r}, \lambda(c,d,\beta_1,\beta_2,\alpha,|v_-|,|x_-|,r)\right) \\ & \leq \mu(c,d,\tilde{\beta},\alpha,|v_-|,|x_-|,r) = \frac{1}{\sqrt{1+|v_-|^2/(4(c^2-|v_-|^2))}} \\ & \quad \times \frac{2^{2\alpha+6}(1+3\tilde{\beta}/c)d^2\sqrt{d}\tilde{\beta}(|v_-|/\sqrt{2}+1-r)^3}{r(\alpha-1)(|v_-|/\sqrt{2}-r)^4(1+|x_-|/\sqrt{2})^{\alpha-1}} \end{aligned} \quad (2.9b)$$

for $T \leq +\infty$, where $\tilde{\beta} = \max(\beta_1, \beta_2)$, $0 < r \leq 1$, $r < c/\sqrt{2}$, $|v_-| < c$, $|v_-| \geq z_1(c, d, \beta_1, \alpha, |x_-|, r)$, $v_-x_- = 0$.

From Lemma 2.1 and the estimates (2.9) we obtain the following result.

Corollary 2.1: Under the conditions (1.2), $0 < r \leq 1$, $r < c/\sqrt{2}$, $|v_-| < c$, $|v_-| \geq z_1(c, d, \beta_1, \alpha, |x_-|, r)$, $v_-x_- = 0$, the following result is valid:

if $\mu_T(c, d, \tilde{\beta}, \alpha, |v_-|, |x_-|, r) < 1$, then $A_{v_-x_-}$ is a contraction map in $M_{T,r}$ for $T \leq 0$;

if $\mu(c, d, \tilde{\beta}, \alpha, |v_-|, |x_-|, r) < 1$, then $A_{v_-x_-}$ is a contraction map in $M_{T,r}$ for $T \leq +\infty$.

Taking into account (2.6) and using Lemma 2.1, Corollary 2.1 and the lemma about the contraction maps we will study the solution $y_-(t)$ of the equation (2.3) in $M_{T,r}$.

We will use also the following results.

Lemma 2.2: Under the conditions (1.2), $f \in M_{T,r}$, $0 < r \leq 1$, $r < c/\sqrt{2}$, $|v_-| < c$, $|v_-| \geq z_1(c, d, \beta_1, \alpha, |x_-|, r)$, $v_-x_- = 0$, the following is valid:

$$\begin{aligned} |\dot{A}_{v_-x_-}(f)(t)| & \leq \zeta_-(c, d, \beta_1, \alpha, |v_-|, |x_-|, r, t) = \frac{1}{\sqrt{1+|v_-|^2/(4(c^2-|v_-|^2))}} \\ & \quad \times \frac{d\beta_1 2^{\alpha+1}}{\alpha(|v_-|/\sqrt{2}-r)(1+|x_-|/\sqrt{2}-(|v_-|/\sqrt{2}-r)t)^\alpha}, \end{aligned} \quad (2.10)$$

$$\begin{aligned} |A_{v_-x_-}(f)(t)| & \leq \xi_-(c, d, \beta_1, \alpha, |v_-|, |x_-|, r, t) = \frac{1}{\sqrt{1+|v_-|^2/(4(c^2-|v_-|^2))}} \\ & \quad \times \frac{d\beta_1 2^{\alpha+1}}{(\alpha-1)\alpha(|v_-|/\sqrt{2}-r)^2(1+|x_-|/\sqrt{2}-(|v_-|/\sqrt{2}-r)t)^{\alpha-1}}, \end{aligned} \quad (2.11)$$

for $t \leq T$, $T \leq 0$;

$$A_{v_-x_-}(f)(t) = k_{v_-x_-}(f)t + l_{v_-x_-}(f) + H_{v_-x_-}(f)(t), \quad (2.12)$$

where

$$k_{v_-x_-}(f) = g\left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_- + f(s))ds\right) - v_-, \quad (2.13a)$$

$$\begin{aligned}
l_{v_{-}x_{-}}(f) &= \int_{-\infty}^0 \left[g\left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f(s))ds\right) - v_{-} \right] d\tau \\
&+ \int_0^{+\infty} \left[g\left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f(s))ds\right) \right. \\
&\left. - g\left(\gamma(v_{-}) + \int_{-\infty}^{+\infty} F(v_{-}s + x_{-} + f(s))ds\right) \right] d\tau, \quad (2.13b)
\end{aligned}$$

$$|k_{v_{-}x_{-}}(f)| \leq 2\xi_{-}(c, d, \beta_1, \alpha, |v_{-}|, |x_{-}|, r, 0), \quad (2.14a)$$

$$|l_{v_{-}x_{-}}(f)| \leq 2\xi_{-}(c, d, \beta_1, \alpha, |v_{-}|, |x_{-}|, r, 0), \quad (2.14b)$$

$$\begin{aligned}
|\dot{H}_{v_{-}x_{-}}(f)(t)| &\leq \zeta_{+}(c, d, \beta_1, \alpha, |v_{-}|, |x_{-}|, r, t) = \frac{1}{\sqrt{1 + |v_{-}|^2/(4(c^2 - |v_{-}|^2))} \alpha (|v_{-}|/\sqrt{2} - r)} \\
&\times \frac{d\beta_1 2^{\alpha+1}}{(1 + |x_{-}|/\sqrt{2} + (|v_{-}|/\sqrt{2} - r)t)^{\alpha}}, \quad (2.15)
\end{aligned}$$

$$\begin{aligned}
|H_{v_{-}x_{-}}(f)(t)| &\leq \xi_{+}(c, d, \beta_1, \alpha, |v_{-}|, |x_{-}|, r, t) = \frac{1}{\sqrt{1 + |v_{-}|^2/(4(c^2 - |v_{-}|^2))} \alpha (\alpha - 1) (|v_{-}|/\sqrt{2} - r)^2} \\
&\times \frac{d\beta_1 2^{\alpha+1}}{(1 + |x_{-}|/\sqrt{2} + (|v_{-}|/\sqrt{2} - r)t)^{\alpha-1}}, \quad (2.16)
\end{aligned}$$

for $T = +\infty$, $t \geq 0$.

Lemma 2.3: Let the conditions (1.2) be valid, $y_{-}(t) \in M_{T,r}$ be a solution of (2.3), $T = +\infty$, $0 < r \leq 1$, $r < c/\sqrt{2}$, $|v_{-}| < c$, $|v_{-}| \geq z_1(c, d, \beta_1, \alpha, |x_{-}|, r)$, $v_{-}x_{-} = 0$, then

$$\begin{aligned}
|k_{v_{-}x_{-}}(y_{-}) - k_{v_{-}x_{-}}(0)| &\leq \varepsilon'_d(c, d, \beta_1, \beta_2, \alpha, |v_{-}|, |x_{-}|, r) = \frac{d\sqrt{d}\beta_2 2^{\alpha+3} (|v_{-}|/\sqrt{2} + 1 - r)}{\alpha (|v_{-}|/\sqrt{2} - r)^2 (1 + |x_{-}|/\sqrt{2})^{\alpha}} \\
&\times \frac{\rho(c, d, \beta_1, \alpha, |v_{-}|, |x_{-}|, r)}{\sqrt{1 + |v_{-}|^2/(4(c^2 - |v_{-}|^2))}}, \quad (2.17a)
\end{aligned}$$

$$\begin{aligned}
\left| \frac{k_{v_{-}x_{-}}(y_{-})}{\sqrt{1 - \frac{|v_{-}|^2}{c^2}}} - \int_{-\infty}^{+\infty} F(x_{-} + v_{-}s) ds \right| &\leq \varepsilon_d(c, d, \beta_1, \beta_2, \alpha, |v_{-}|, |x_{-}|, r) \\
&= \frac{d\beta_2 2^{\alpha+3} (1 + |v_{-}|/\sqrt{2} - r) \rho(c, d, \beta_1, \alpha, |v_{-}|, |x_{-}|, r)}{\alpha (|v_{-}|/\sqrt{2} - r)^2 (1 + |x_{-}|/\sqrt{2})^{\alpha}}, \quad (2.17b)
\end{aligned}$$

$$\begin{aligned}
|l_{v_{-}x_{-}}(y_{-}) - l_{v_{-}x_{-}}(0)| &\leq \varepsilon_b(c, d, \beta_1, \beta_2, \alpha, |v_{-}|, |x_{-}|, r) = \frac{d^2 \sqrt{d} (\beta_2 + 3\beta_1 \beta_2 / c) 2^{2\alpha+6} (|v_{-}|/\sqrt{2} + 1 - r)^2}{\alpha (\alpha - 1) (|v_{-}|/\sqrt{2} - r)^4 (1 + |x_{-}|/\sqrt{2})^{\alpha-1}} \\
&\times \frac{\rho(c, d, \beta_1, \alpha, |v_{-}|, |x_{-}|, r)}{\sqrt{1 + |v_{-}|^2/(4(c^2 - |v_{-}|^2))}}. \quad (2.17c)
\end{aligned}$$

Proofs of Lemmas 2.1, 2.2, 2.3 are given in Sec. V.

III. SMALL ANGLE SCATTERING

Under the conditions (1.2), for any $(v_-, x_-) \in B_c \times \mathbb{R}^d$, $v_- \neq 0$, the equation (1.1) has a unique solution $x \in C^2(\mathbb{R}, \mathbb{R}^d)$ with the initial conditions (1.3). Consider the function $y_-(t)$ from (1.3). This function describes deflection from free motion.

Using Corollary 2.1 the lemma about contraction maps, and Lemmas 2.2 and 2.3 we obtain the following result.

Theorem 3.1: *Let the conditions (1.2) be valid, $\mu(c, d, \tilde{\beta}, \alpha, |v_-|, |x_-|, r) < 1$, $\tilde{\beta} = \max(\beta_1, \beta_2)$, $0 < r \leq 1$, $r < c/\sqrt{2}$, $|v_-| < c$, $|v_-| \geq z_1(c, d, \beta_1, \alpha, |x_-|, r)$, $v_- x_- = 0$. Then the deflection $y_-(t)$ has the following properties:*

$$y_- \in M_{T,r}, \quad T = +\infty, \quad (3.1)$$

$$|\dot{y}_-(t)| \leq \zeta_-(c, d, \beta_1, \alpha, |v_-|, |x_-|, r, t), \quad (3.2)$$

$$|y_-(t)| \leq \xi_-(c, d, \beta_1, \alpha, |v_-|, |x_-|, r, t) \quad \text{for } t \leq 0, \quad (3.3)$$

$$y_-(t) = a_{sc}(v_-, x_-)t + b_{sc}(v_-, x_-) + h(v_-, x_-, t), \quad (3.4)$$

where

$$\left| a_{sc}(v_-, x_-) - \left[\frac{\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_-) ds}{\sqrt{1 + \frac{|\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_-) ds|^2}{c^2}}} - v_- \right] \right| \leq \varepsilon'_a(c, d, \beta_1, \beta_2, \alpha, |v_-|, |x_-|, r), \quad (3.5a)$$

$$\left| \frac{a_{sc}(v_-, x_-)}{\sqrt{1 - \frac{|v_-|^2}{c^2}}} - \int_{-\infty}^{+\infty} F(v_-s + x_-) ds \right| \leq \varepsilon_a(c, d, \beta_1, \beta_2, \alpha, |v_-|, |x_-|, r), \quad (3.5b)$$

$$|b_{sc}(v_-, x_-) - l_{v_-, x_-}(0)| \leq \varepsilon_b(c, d, \beta_1, \beta_2, \alpha, |v_-|, |x_-|, r), \quad (3.5c)$$

$$|a_{sc}(v_-, x_-)| \leq 2\zeta_-(c, d, \beta_1, \alpha, |v_-|, |x_-|, r, 0), \quad (3.6a)$$

$$|b_{sc}(v_-, x_-)| \leq 2\xi_-(c, d, \beta_1, \alpha, |v_-|, |x_-|, r, 0), \quad (3.6b)$$

$$|\dot{h}(v_-, x_-, t)| \leq \zeta_+(c, d, \beta_1, \alpha, |v_-|, |x_-|, r, t), \quad (3.7)$$

$$|h(v_-, x_-, t)| \leq \xi_+(c, d, \beta_1, \alpha, |v_-|, |x_-|, r, t) \quad (3.8)$$

for $t \geq 0$, where $l_{v_-, x_-}(0)$ (respectively, ε'_a , ε_a , ε_b , ζ_- , ζ_+ , ξ_- and ξ_+) is defined in (2.13b) [respectively, (2.17a), (2.17b), (2.17c), (2.10), (2.15), (2.11), and (2.16)].

We will use the following observations.

(I) Let $0 < r \leq 1$, $r < c/\sqrt{2}$, $0 \leq u$,

$$\frac{s_1}{\sqrt{1-\frac{s_1^2}{c^2}}} - \frac{2^{\alpha+4}\beta_1\sqrt{d}}{\alpha(s_1/\sqrt{2}-r)(u/\sqrt{2}+1)^\alpha} > \frac{s_2}{\sqrt{1-\frac{s_2^2}{c^2}}} - \frac{2^{\alpha+4}\beta_1\sqrt{d}}{\alpha(s_2/\sqrt{2}-r)(u/\sqrt{2}+1)^\alpha}$$

for $\sqrt{2}r < s_2 < s_1 < c$.

(II) Let $0 < r \leq 1$, $r < c/\sqrt{2}$, $u \in]\sqrt{2}r, c[$,

$$\frac{u}{\sqrt{1-\frac{u^2}{c^2}}} - \frac{2^{\alpha+4}\beta_1\sqrt{d}}{\alpha(u/\sqrt{2}-r)(s_1/\sqrt{2}+1)^\alpha} > \frac{u}{\sqrt{1-\frac{u^2}{c^2}}} - \frac{2^{\alpha+4}\beta_1\sqrt{d}}{\alpha(u/\sqrt{2}-r)(s_2/\sqrt{2}+1)^\alpha}$$

for $0 \leq s_2 < s_1$.

(III) Let $0 < r \leq 1$, $r < c/\sqrt{2}$, x some real non-negative number, $\tilde{\beta} = \max(\beta_1, \beta_2)$ and $\sqrt{2}r < s < c$ then

$$\mu(c, d, \tilde{\beta}, \alpha, s, |x|, r) < 1 \quad s > z(c, d, \tilde{\beta}, \alpha, |x|, r).$$

Observations (I) and (II) imply that $z_1(c, d, \beta_1, \alpha, s_2, r) > z_1(c, d, \beta_1, \alpha, s_1, r)$ for $\sqrt{2}r < s_2 < s_1 < c$ when c, β_1, α, d, r are fixed.

Theorem 3.1 gives, in particular, estimates for the scattering process and asymptotics for the velocity valued component of the scattering map when $c, \beta_1, \beta_2, \alpha, d, \hat{v}_-, x_-$ are fixed (where $\hat{v}_- = v_-/|v_-|$) and $|v_-|$ increases or, e.g., $c, \beta_1, \beta_2, \alpha, v_-, \hat{x}_-$ are fixed and $|x_-|$ increases. In these cases $\sup_{t \in \mathbb{R}} |\theta(t)|$ decreases, where $\theta(t)$ denotes the angle between the vectors $\dot{x}(t) = v_- + \dot{y}_-(t)$ and v_- , and we deal with small angle scattering. Note that already under the conditions of Theorem 3.1, without additional assumptions, there is the estimate $\sup_{t \in \mathbb{R}} |\theta(t)| < \frac{1}{4}\pi$ and we deal with a rather small angle scattering. Theorem 3.1 with (3.5c) will give the asymptotics of the configuration valued component $b(v_-, x_-)$ of the scattering map if we can study the asymptotics of $l_{v_-, x_-}(0)$. This is the subject of Theorem 3.2.

Theorem 3.2: Let $c, d, \beta_0, \beta_1, \alpha, |x|$ be fixed. Then there exists a constant $C_{c,d,\beta_0,\beta_1,\alpha,|x|}$ such that

$$\left| \frac{l_{v,x}(0)}{\sqrt{1-\frac{|v|^2}{c^2}}} - \frac{1}{c^2} PV(\hat{v}, x) \hat{v} + \frac{1}{|v|^2} \int_0^{+\infty} \int_\tau^{+\infty} F(u\hat{v} + x) du d\tau - \frac{1}{|v|^2} \int_{-\infty}^0 \int_{-\infty}^\tau F(u\hat{v} + x) du d\tau \right| \leq C_{c,d,\beta_0,\beta_1,\alpha,|x|} \sqrt{1-\frac{|v|^2}{c^2}} \tag{3.9}$$

for any $v \in B_c$, $|v| \geq z_2(c, d, \beta_1, \alpha, |x|)$, $vx=0$, and where $\hat{v} = v/|v|$.

The proof of Theorem 3.2 is given in Sec. VI. Using this proof one can compute $C_{c,d,\beta_0,\beta_1,\alpha,|x|}$ explicitly.

IV. PRELIMINARIES FOR THE MAIN PROOFS

A. Inequalities for F

Lemma 4.1: Under the conditions (1.2), the following estimates are valid:

$$|F(x)| = \left(\sum_{j=1}^d \left| \frac{\partial}{\partial x_j} V(x) \right|^2 \right)^{1/2} \leq \beta_1 \sqrt{d} (1 + |x|)^{-(\alpha+1)} \quad \text{for } x \in \mathbb{R}^d, \tag{4.1}$$

$$|F(x) - F(y)| \leq \beta_2 d \sup_{\varepsilon \in [0,1]} (1 + |\varepsilon x + (1-\varepsilon)y|)^{-(\alpha+2)} |x - y|, \quad \text{for } x, y \in \mathbb{R}^d. \tag{4.2}$$

Lemma 4.1 follows directly from the formula $F(x) = -\nabla V(x)$ and the conditions (1.2).

B. Infinitely smooth function $g: \mathbb{R}^d \rightarrow \mathcal{B}_c$

Lemma 4.2: The following estimates hold:

$$|\nabla g_i(x)|^2 \leq \frac{1}{1 + \frac{|x|^2}{c^2}} \quad \text{for } x \in \mathbb{R}^d, \quad i = 1, \dots, d, \quad (4.3)$$

$$|g(x) - g(y)| \leq \sqrt{d} \sup_{\varepsilon \in [0,1]} \frac{1}{\sqrt{1 + \frac{|\varepsilon x + (1-\varepsilon)y|^2}{c^2}}} |x - y| \quad \text{for } x, y \in \mathbb{R}^d, \quad (4.4)$$

$$|\nabla g_i(x) - \nabla g_i(y)| \leq \frac{3\sqrt{d}}{c} \sup_{\varepsilon \in [0,1]} \frac{1}{1 + \frac{|\varepsilon x + (1-\varepsilon)y|^2}{c^2}} |x - y| \quad \text{for } x, y \in \mathbb{R}^d, \quad (4.5)$$

where $g = (g_1, \dots, g_d)$.

Lemma 4.2 follows from straightforward calculations.

Remark 4.1: Using the growth properties of $g(p)$ with respect to $|p|$ and following Novikov's framework,⁷ we will easily generalize some of the results of Ref. 7 to the relativistic case. Note that $1/(1 + |p|^2/c^2) \rightarrow 0$ when $p \in \mathbb{R}^d$, $|p| \rightarrow +\infty$.

C. Some estimates of integrals

We will use the following estimates. For $a > 0$, $b > 0$, $\beta > 1$,

$$\int_{-\infty}^t (a + b|s|)^{-\beta} ds = \frac{1}{(\beta - 1)b(a - bt)^{\beta-1}} \quad \text{for } t \leq 0, \quad (4.6)$$

$$\int_{-\infty}^t (a + b|s|)^{-\beta} ds \leq \frac{2}{(\beta - 1)ba^{\beta-1}} \quad \text{for } t \geq 0. \quad (4.7)$$

For $a > 0$, $b > 0$, $\beta > 2$,

$$\int_{-\infty}^t \int_{-\infty}^{\tau} (a + b|s|)^{-\beta} ds d\tau = \frac{1}{(\beta - 2)(\beta - 1)b^2(a - bt)^{\beta-2}} \quad \text{for } t \leq 0, \quad (4.8)$$

$$\int_0^t \int_{\tau}^t (a + bs)^{-\beta} ds d\tau \leq \frac{1}{(\beta - 2)(\beta - 1)b^2a^{\beta-2}} \quad \text{for } t \geq 0. \quad (4.9)$$

For $a \geq 1$, $b > 0$, $\beta > 2$,

$$\int_{-\infty}^t (a + b|s|)^{-\beta}(1 + |s|) ds \leq \frac{b + 1}{(\beta - 2)b^2(a - bt)^{\beta-2}} \quad \text{for } t \leq 0, \quad (4.10)$$

$$\int_{-\infty}^t (a + b|s|)^{-\beta}(1 + |s|) ds \leq 2 \frac{b + 1}{(\beta - 2)b^2a^{\beta-2}} \quad \text{for } t \geq 0. \quad (4.11)$$

For $a \geq 1$, $b > 0$, $\beta > 3$,

$$\int_0^t \int_\tau^t (a + bs)^{-\beta} (1 + s) ds d\tau \leq \frac{b + 1}{(\beta - 3)(\beta - 2)b^3 a^{\beta-3}} \quad \text{for } t \geq 0. \tag{4.12}$$

For the proof of (4.6)–(4.12), see Ref. 7.

D. About $z_1(c, d, \beta_1, \alpha, |x_-|, r)$

Let $c, d, \beta_1, \alpha, |x_-|, 0 < r \leq 1, r < c/\sqrt{2}$, be fixed. We consider the one-dimensional infinitely smooth function $\sigma:]\sqrt{2}r, c[\rightarrow \mathbb{R}$ defined by

$$\sigma(s) = \frac{s}{\sqrt{1 - \frac{s^2}{c^2}}} - \frac{2^{\alpha+4} \beta_1 \sqrt{d}}{\alpha (s/\sqrt{2} - r) (|x_-|/\sqrt{2} + 1)^\alpha}.$$

σ is an increasing function (its derivative is a positive function) and as a consequence $z_1(c, d, \beta_1, \alpha, |x_-|, r)$ is well defined in the Introduction and the observation (I) of Sec. III holds.

E. About $M_{T,r}, 0 < r \leq 1, r < c/\sqrt{2}$

Lemma 4.3: Let $f, f_1, f_2 \in M_{T,r}, v_- \in B_c \setminus \{0\}, v_- x_- = 0, |v_-| > \sqrt{2}r$, then

$$\varepsilon f_1 + (1 - \varepsilon) f_2 \in M_{T,r} \quad \text{for } 0 \leq \varepsilon \leq 1, \tag{4.13}$$

$$2(1 + |x_- + v_- s + f(s)|) \geq (1 + |x_-|/\sqrt{2} + (|v_-|/\sqrt{2} - r)|s|) \quad \text{for } s \leq T, \tag{4.14}$$

$$\left| \int_{-\infty}^t F(v_- s + x_- + f(s)) ds \right| \leq \frac{\beta_1 \sqrt{d} 2^{\alpha+2}}{\alpha (|v_-|/\sqrt{2} - r) (|x_-|/\sqrt{2} + 1)^\alpha} \quad \text{for } t \in]-\infty, +\infty], \tag{4.15}$$

$$\begin{aligned} & \left(1 + \frac{1}{c^2} \left| \gamma(v_-) + \varepsilon_1 \int_{-\infty}^t F(v_- s + x_- + f_1(s)) ds + \varepsilon_2 \int_w^u F(v_- s + x_- + f_2(s)) ds \right|^2 \right)^{-\beta} \\ & \leq \left(1 + \frac{|v_-|^2}{4(c^2 - |v_-|^2)} \right)^{-\beta}, \end{aligned} \tag{4.16}$$

for $u, t \in]-\infty, T], w \in]-\infty, u], \beta > 0, -1 \leq \varepsilon_1, \varepsilon_2 \leq 1, f_1, f_2 \in M_{T,r}$ and if $|v_-| \geq z_1(c, d, \beta_1, \alpha, |x_-|, r), |v_-| < c$, where γ is defined by

$$\gamma(v) = \frac{v}{\sqrt{1 - |v|^2/c^2}},$$

for $v \in B_c$.

Proof of Lemma 4.3: For the proof of (4.14) see Ref. 7. Inequality (4.1) with (4.14) and (4.7) proves (4.15). (4.13) follows from the definition of $M_{T,r}$. Inequality (4.15) gives in particular for $u, t \in]-\infty, T], w \in]-\infty, u], \beta > 0, -1 \leq \varepsilon_1, \varepsilon_2 \leq 1, f_1, f_2 \in M_{T,r}$,

$$\begin{aligned} & \left| \gamma(v_-) + \varepsilon_1 \int_{-\infty}^t F(v_- s + x_- + f_1(s)) ds + \varepsilon_2 \int_w^u F(v_- s + x_- + f_2(s)) ds \right| \\ & \geq |\gamma(v_-)| - \frac{\beta_1 \sqrt{d} 2^{\alpha+3}}{\alpha (|v_-|/\sqrt{2} - r) (|x_-|/\sqrt{2} + 1)^\alpha} \end{aligned}$$

$$\begin{aligned}
&= \frac{|v_-|}{\sqrt{1-|v_-|^2/c^2}} - \frac{\beta_1 \sqrt{d} 2^{\alpha+3}}{\alpha(|v_-|/\sqrt{2}-r)(|x_-|/\sqrt{2}+1)^\alpha} \\
&\geq \frac{c|v_-|}{2\sqrt{c^2-|v_-|^2}} \quad \text{if } |v_-| \geq z_1(c,d,\beta_1,\alpha,|x_-|,r), \quad |v_-| < c,
\end{aligned}$$

which implies (4.16).

V. PROOFS OF LEMMAS 2.1, 2.2, 2.3

Proof of Lemma 2.1: The property

$$A_{v_-,x_-}(f) \in C^1([-\infty, T], \mathbb{R}^d) \quad \text{for } f \in M_{T,r} \quad (0 < r \leq 1, r < |v_-|/\sqrt{2}) \quad (5.1)$$

follows from (1.2) and (2.1) [applied on “ x ” = $\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_- + f(s))ds$ and “ y ” = $\gamma(v_-)$] and the definition of $A_{v_-,x_-}(f)$.

Now we always suppose that $0 < r \leq 1$, $r < c/\sqrt{2}$, $|v_-| \geq z_1(c,d,\beta_1,\alpha,|x_-|,r)$, $|v_-| < c$, $v_-x_- = 0$. Consider

$$\begin{aligned}
A_{v_-,x_-}(f)(t) &= \int_{-\infty}^t \left[g \left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_- + f(s))ds \right) - v_- \right] d\tau \\
\frac{d}{dt} A_{v_-,x_-}(f)(t) &= g \left(\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_- + f(s))ds \right) - v_-.
\end{aligned} \quad \text{for } f \in M_{T,r}, \quad (5.2)$$

First we shall prove some estimates about $(d/dt)A_{v_-,x_-}(f)$.

Note that $g(\gamma(v_-)) = v_-$. From (5.2) and (4.4) [applied on “ x ” = $\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_- + f(s))ds$ and “ y ” = $\gamma(v_-)$], (4.1), (4.14), and (4.16) it follows that

$$\left| \frac{d}{dt} A_{v_-,x_-}(f)(t) \right| \leq \frac{d\beta_1 2^{\alpha+1}}{\sqrt{1 + \frac{|v_-|^2}{4(c^2 - |v_-|^2)}}} \int_{-\infty}^t (1 + |x_-|/\sqrt{2} + (|v_-|/\sqrt{2} - r)|s|)^{-(\alpha+1)} ds. \quad (5.3)$$

Our next purpose is to prove estimates (5.5) and (5.9) given below.

From (5.3), (4.8), and (4.6) it follows that

$$|A_{v_-,x_-}(f)(t)| \leq \frac{d\beta_1 2^{\alpha+1}}{\sqrt{1 + \frac{|v_-|^2}{4(c^2 - |v_-|^2)}}} \alpha(\alpha-1) \left(\frac{|v_-|}{\sqrt{2}} - r \right)^2 \left(1 + \frac{|x_-|}{\sqrt{2}} - \left(\frac{|v_-|}{\sqrt{2}} - r \right) t \right)^{\alpha-1}, \quad (5.4a)$$

$$\left| t \frac{d}{dt} A_{v_-,x_-}(f)(t) \right| \leq \frac{d\beta_1 2^{\alpha+1}}{\sqrt{1 + \frac{|v_-|^2}{4(c^2 - |v_-|^2)}}} \alpha \left(\frac{|v_-|}{\sqrt{2}} - r \right)^2 \left(1 + \frac{|x_-|}{\sqrt{2}} - \left(\frac{|v_-|}{\sqrt{2}} - r \right) t \right)^{\alpha-1}, \quad (5.4b)$$

for $t \leq T$, $t \leq 0$. From (5.4) it follows that

$$\left| A_{v_{-}x_{-}}(f)(t) - t \frac{d}{dt} A_{v_{-}x_{-}}(f)(t) \right| \leq \frac{d\beta_1 2^{\alpha+1}}{\sqrt{1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}} (\alpha - 1)(|v_{-}|/\sqrt{2} - r)^2 (1 + |x_{-}|/\sqrt{2} - (|v_{-}|/\sqrt{2} - r)t)^{\alpha-1}}, \tag{5.5}$$

for $t \leq T, t \leq 0$.

For $t \leq T, t \geq 0$, note that

$$A_{v_{-}x_{-}}(f)(t) - t \frac{d}{dt} A_{v_{-}x_{-}}(f)(t) = A_{v_{-}x_{-}}(f)(0) + \int_0^t \left[g \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f(s)) ds \right) - g \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f(s)) ds \right) \right] d\tau. \tag{5.6}$$

For $A_{v_{-}x_{-}}(f)(0)$ we use the estimate (5.4a), i.e.,

$$|A_{v_{-}x_{-}}(f)(0)| \leq \frac{d\beta_1 2^{\alpha+1}}{\sqrt{1 + (|v_{-}|^2/(4(c^2 - |v_{-}|^2)))} \alpha(\alpha - 1)(|v_{-}|/\sqrt{2} - r)^2 (1 + |x_{-}|/\sqrt{2})^{\alpha-1}}. \tag{5.7}$$

We estimate the second term on the right-hand side of (5.6) in the following way: from (4.4), (4.16), (4.1), (4.14), and (4.9), it follows that

$$\begin{aligned} & \left| \int_0^t \left[g \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f(s)) ds \right) - g \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f(s)) ds \right) \right] d\tau \right| \\ & \leq \frac{\sqrt{d}}{\sqrt{1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}}} \int_0^t \left| \int_{\tau}^{\tau} F(v_{-}s + x_{-} + f(s)) ds \right| d\tau \\ & \leq \frac{d\beta_1 2^{\alpha+1}}{\sqrt{1 + (|v_{-}|^2/(4(c^2 - |v_{-}|^2)))} \alpha(\alpha - 1)(|v_{-}|/\sqrt{2} - r)^2 (1 + |x_{-}|/\sqrt{2})^{\alpha-1}}, \end{aligned} \tag{5.8}$$

for $0 \leq t \leq T$. From (5.6)–(5.8) it follows that

$$\left| A_{v_{-}x_{-}}(f)(t) - t \frac{d}{dt} A_{v_{-}x_{-}}(f)(t) \right| \leq \frac{d\beta_1 2^{\alpha+2}}{\sqrt{1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}} \alpha(\alpha - 1)(|v_{-}|/\sqrt{2} - r)^2 (1 + |x_{-}|/\sqrt{2})^{\alpha-1}}, \tag{5.9}$$

for $0 \leq t \leq T$. Using (5.3) and (4.6) and using (5.5) we obtain (2.7a). Using (5.3) and (4.7) and using (5.9) we obtain (2.7b).

Our next purpose is to prove estimate (5.14) given below. Consider $(d/dt)(A_{v_{-}x_{-}}(f_2)(t) - A_{v_{-}x_{-}}(f_1)(t))$ for $f_1, f_2 \in M_{T,r} [0 < r \leq 1, r < c/\sqrt{2}, |v_{-}| < c, v_{-}x_{-} = 0, |v_{-}| \geq z_1(c, d, \beta_1, \alpha, |x_{-}|, r)]$. First

$$\begin{aligned} \frac{d}{dt} A_{v_{-}x_{-}}(f_2)(t) - \frac{d}{dt} A_{v_{-}x_{-}}(f_1)(t) &= g \left(\gamma(v_{-}) + \int_{-\infty}^t F(v_{-}s + x_{-} + f_2(s)) ds \right) \\ &\quad - g \left(\gamma(v_{-}) + \int_{-\infty}^t F(v_{-}s + x_{-} + f_1(s)) ds \right) \end{aligned} \tag{5.10}$$

for $t \leq T$. From (5.10), (4.4), and (4.16) it follows that

$$\left| \frac{d}{dt} A_{v_{-}x_{-}}(f_2)(t) - \frac{d}{dt} A_{v_{-}x_{-}}(f_1)(t) \right| \leq \frac{\sqrt{d}}{\sqrt{1 + (|v_{-}|^2/(4(c^2 - |v_{-}|^2)))}} \int_{-\infty}^t |F(v_{-}s + x_{-} + f_2(s)) - F(v_{-}s + x_{-} + f_1(s))| ds, \quad (5.11)$$

for $t \leq T$. From (4.13), (4.14), and (4.2), it follows that

$$|F(v_{-}s + x_{-} + f_2(s)) - F(v_{-}s + x_{-} + f_1(s))| \leq d\beta_2 2^{\alpha+2} (1 + |x_{-}|/\sqrt{2} + (|v_{-}|/\sqrt{2} - r)|s|)^{-(\alpha+2)} |f_2(s) - f_1(s)| \quad \text{for } s \leq T. \quad (5.12)$$

Moreover

$$|f_2(s) - f_1(s)| \leq (1 + |s|) \|f_2 - f_1\|_T \quad \text{for } s \leq T. \quad (5.13)$$

Thus, from (5.11)–(5.13) it follows that

$$\left| \frac{d}{dt} A_{v_{-}x_{-}}(f_2)(t) - \frac{d}{dt} A_{v_{-}x_{-}}(f_1)(t) \right| \leq \frac{d\sqrt{d}\beta_2 2^{\alpha+2} \|f_2 - f_1\|_T}{\sqrt{1 + (|v_{-}|^2/(4(c^2 - |v_{-}|^2)))}} \int_{-\infty}^t (1 + |x_{-}|/\sqrt{2} + (|v_{-}|/\sqrt{2} - r)|s|)^{-(\alpha+2)} (1 + |s|) ds. \quad (5.14)$$

Our next purpose is to prove estimates (5.17) and (5.31) given below. From (5.14), (4.10), and (4.6) it follows that

$$\begin{aligned} & |A_{v_{-}x_{-}}(f_2)(t) - A_{v_{-}x_{-}}(f_1)(t)| \\ & \leq \frac{d\sqrt{d}\beta_2 2^{\alpha+2} (|v_{-}|/\sqrt{2} + 1 - r) \|f_2 - f_1\|_T}{\sqrt{1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}} \alpha(\alpha - 1) (|v_{-}|/\sqrt{2} - r)^3 (1 + |x_{-}|/\sqrt{2} - (|v_{-}|/\sqrt{2} - r)t)^{\alpha-1}} \end{aligned} \quad (5.15)$$

for $t \leq T$, $t \leq 0$. From (5.14) and (4.10) it also follows that

$$\begin{aligned} & \left| t \left[\frac{d}{dt} A_{v_{-}x_{-}}(f_2)(t) - \frac{d}{dt} A_{v_{-}x_{-}}(f_1)(t) \right] \right| \\ & \leq \frac{d\sqrt{d}\beta_2 2^{\alpha+2} (|v_{-}|/\sqrt{2} + 1 - r) \|f_2 - f_1\|_T}{\sqrt{1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}} \alpha (|v_{-}|/\sqrt{2} - r)^3 (1 + |x_{-}|/\sqrt{2} - (|v_{-}|/\sqrt{2} - r)t)^{\alpha-1}} \end{aligned} \quad (5.16)$$

for $t \leq T$, $t \leq 0$. Hence from (5.15) and (5.16) it follows that

$$\begin{aligned} & \left| A_{v_{-}x_{-}}(f_2)(t) - A_{v_{-}x_{-}}(f_1)(t) - t \frac{d}{dt} (A_{v_{-}x_{-}}(f_2)(t) - A_{v_{-}x_{-}}(f_1)(t)) \right| \\ & \leq \frac{d\sqrt{d}\beta_2 2^{\alpha+2} (|v_{-}|/\sqrt{2} + 1 - r) \|f_2 - f_1\|_T}{\sqrt{1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}} (\alpha - 1) (|v_{-}|/\sqrt{2} - r)^3 (1 + |x_{-}|/\sqrt{2} - (|v_{-}|/\sqrt{2} - r)t)^{\alpha-1}} \end{aligned} \quad (5.17)$$

for $t \leq T$, $t \leq 0$.

For $0 \leq t \leq T$, using (5.6) we obtain

$$\begin{aligned}
 & \left| A_{v_{-},x_{-}}(f_2)(t) - A_{v_{-},x_{-}}(f_1)(t) - t \left(\frac{d}{dt} A_{v_{-},x_{-}}(f_2)(t) - \frac{d}{dt} A_{v_{-},x_{-}}(f_1)(t) \right) \right| \leq |A_{v_{-},x_{-}}(f_2)(0) - A_{v_{-},x_{-}}(f_1)(0)| \\
 & + \left| \int_0^t \left[g \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_2(s)) ds \right) - g \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_1(s)) ds \right) \right. \right. \\
 & \left. \left. - g \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_1(s)) ds \right) + g \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_2(s)) ds \right) \right] d\tau \right|.
 \end{aligned}
 \tag{5.18}$$

From (5.15) it follows that

$$|A_{v_{-},x_{-}}(f_2)(0) - A_{v_{-},x_{-}}(f_1)(0)| \leq \frac{d\sqrt{d}\beta_2 2^{\alpha+2} (|v_{-}|/\sqrt{2} + 1 - r) \|f_2 - f_1\|_T}{\sqrt{1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}} \alpha(\alpha - 1) \left(\frac{|v_{-}|}{\sqrt{2}} - r\right)^3 \left(1 + \frac{|x_{-}|}{\sqrt{2}}\right)^{\alpha-1}}.
 \tag{5.19}$$

In order to estimate the second term of the right-hand side of (5.18), we will estimate

$$\begin{aligned}
 & \int_0^t \left[g_j \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_2(s)) ds \right) - g_j \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_1(s)) ds \right) \right. \\
 & \left. - g_j \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_1(s)) ds \right) + g_j \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_2(s)) ds \right) \right] d\tau
 \end{aligned}
 \tag{5.20}$$

for $1 \leq j \leq d$ and $0 \leq t \leq T$.

Let $1 \leq j \leq d$ and $0 \leq t \leq T$, $0 \leq \tau \leq t$. Note that

$$\begin{aligned}
 & g_j \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_2(s)) ds \right) - g_j \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_1(s)) ds \right) \\
 & - \left(g_j \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_1(s)) ds \right) - g_j \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_2(s)) ds \right) \right) \\
 & = \Delta_{j,t}^1(\tau) + \Delta_{j,t}^2(\tau),
 \end{aligned}
 \tag{5.21}$$

where

$$\begin{aligned}
 \Delta_{j,t}^1(\tau) &= \int_t^\tau (F(v_{-}s + x_{-} + f_2(s)) - F(v_{-}s + x_{-} + f_1(s))) ds \\
 & \star \int_0^1 \nabla g_j \left(\gamma(v_{-}) + \int_{-\infty}^{\tau} F(v_{-}s + x_{-} + f_2(s)) ds + \varepsilon \int_t^\tau F(v_{-}s + x_{-} + f_2(s)) ds \right) d\varepsilon,
 \end{aligned}
 \tag{5.22a}$$

$$\begin{aligned}
\Delta_{j,i}^2(\tau) &= \int_t^\tau F(v_{-s} + x_{-} + f_1(s)) ds \\
&\star \int_0^1 \left[\nabla g_j \left(\gamma(v_{-}) + \int_{-\infty}^t F(v_{-s} + x_{-} + f_2(s)) ds + \varepsilon \int_t^\tau F(v_{-s} + x_{-} + f_2(s)) ds \right) \right. \\
&\quad \left. - \nabla g_j \left(\gamma(v_{-}) + \int_{-\infty}^t F(v_{-s} + x_{-} + f_1(s)) ds + \varepsilon \int_t^\tau F(v_{-s} + x_{-} + f_1(s)) ds \right) \right] d\varepsilon,
\end{aligned} \tag{5.22b}$$

where \star denotes the usual scalar product on \mathbb{R}^d .

Using (5.22a), (4.3), (4.2), (4.16), (4.14), and (5.13), we obtain

$$|\Delta_{j,i}^1(\tau)| \leq \frac{d\beta_2 2^{\alpha+2}}{\sqrt{1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}}} \int_\tau^t (1 + |x_{-}|/\sqrt{2} + (|v_{-}|/\sqrt{2} - r)s)^{-(\alpha+2)} (1+s) ds \|f_2 - f_1\|_T. \tag{5.23}$$

Thus from (4.12) it follows that

$$\int_0^t |\Delta_{j,i}^1(\tau)| d\tau \leq \frac{d\beta_2 2^{\alpha+2} (|v_{-}|/\sqrt{2} + 1 - r)}{\sqrt{1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}} \alpha(\alpha-1) (|v_{-}|/\sqrt{2} - r)^3 (1 + |x_{-}|/\sqrt{2})^{\alpha-1}} \|f_2 - f_1\|_T. \tag{5.24}$$

Using (5.22b), (4.5), and (4.16), we obtain

$$\begin{aligned}
|\Delta_{j,i}^2(\tau)| &\leq \int_\tau^t |F(v_{-s} + x_{-} + f_1(s))| ds \left[\frac{3\sqrt{d}}{c(1 + (|v_{-}|^2/(4(c^2 - |v_{-}|^2))))} \right. \\
&\quad \times \int_0^1 \left| \int_{-\infty}^t (F(v_{-s} + x_{-} + f_2(s)) - F(v_{-s} + x_{-} + f_1(s))) ds \right. \\
&\quad \left. \left. + \varepsilon \int_t^\tau (F(v_{-s} + x_{-} + f_2(s)) - F(v_{-s} + x_{-} + f_1(s))) ds \right| d\varepsilon \right].
\end{aligned} \tag{5.25}$$

We shall use

$$\begin{aligned}
&\left| \int_{-\infty}^t (F(v_{-s} + x_{-} + f_2(s)) - F(v_{-s} + x_{-} + f_1(s))) ds \right. \\
&\quad \left. + \varepsilon \int_t^\tau (F(v_{-s} + x_{-} + f_2(s)) - F(v_{-s} + x_{-} + f_1(s))) ds \right| \\
&\leq 2 \int_{-\infty}^t |(F(v_{-s} + x_{-} + f_2(s)) - F(v_{-s} + x_{-} + f_1(s)))| ds,
\end{aligned} \tag{5.26}$$

for all $0 \leq \varepsilon \leq 1$ (we remind that $\tau \leq t$).

From (5.25) and (5.26) it follows that

$$\begin{aligned}
|\Delta_{j,i}^2(\tau)| &\leq \int_{\tau}^t |F(v_{-s} + x_{-} + f_1(s))| ds \\
&\quad \times \frac{6\sqrt{d}}{c \left(1 + \frac{|v_{-}|^2}{4(c^2 - |v_{-}|^2)}\right)} \int_{-\infty}^t |(F(v_{-s} + x_{-} + f_2(s)) - F(v_{-s} + x_{-} + f_1(s)))| ds.
\end{aligned} \tag{5.27}$$

Using (4.2), (4.14), (5.13), and (4.11) we obtain

$$\int_{-\infty}^t |F(v_{-s} + x_{-} + f_2(s)) - F(v_{-s} + x_{-} + f_1(s))| ds \leq \frac{d\beta_2 2^{\alpha+3} (|v_{-}|/\sqrt{2} + 1 - r)}{\alpha (|v_{-}|/\sqrt{2} - r)^2 (1 + |x_{-}|/\sqrt{2})^{\alpha}} \|f_2 - f_1\|_T. \tag{5.28}$$

Using (4.1), (4.14), and (4.9) we obtain

$$\int_0^t \int_{\tau}^t |F(v_{-s} + x_{-} + f_1(s))| ds d\tau \leq \frac{\sqrt{d}\beta_1 2^{\alpha+1}}{\alpha(\alpha-1)(|v_{-}|/\sqrt{2} - r)^2 (1 + |x_{-}|/\sqrt{2})^{\alpha-1}}. \tag{5.29}$$

From (5.27)–(5.29) it follows that

$$\int_0^t |\Delta_{j,i}^2(\tau)| d\tau \leq \frac{3}{c(1 + (|v_{-}|^2/(4(c^2 - |v_{-}|^2))))} \frac{d^2\beta_1\beta_2 2^{2\alpha+5} (|v_{-}|/\sqrt{2} + 1 - r)}{\alpha^2(\alpha-1)(|v_{-}|/\sqrt{2} - r)^4 (1 + |x_{-}|/\sqrt{2})^{2\alpha-1}} \|f_2 - f_1\|_T. \tag{5.30}$$

From (5.18), (5.19), (5.21), (5.24), and (5.30), it follows that

$$\begin{aligned}
&\left| A_{v_{-},x_{-}}(f_2)(t) - A_{v_{-},x_{-}}(f_1)(t) - t \left(\frac{d}{dt} A_{v_{-},x_{-}}(f_2)(t) - \frac{d}{dt} A_{v_{-},x_{-}}(f_1)(t) \right) \right| \\
&\leq \frac{d\sqrt{d}\beta_2 2^{\alpha+2} (|v_{-}|/\sqrt{2} + 1 - r)}{\sqrt{1 + (|v_{-}|^2/(4(c^2 - |v_{-}|^2)))} \alpha(\alpha-1)(|v_{-}|/\sqrt{2} - r)^3 (1 + |x_{-}|/\sqrt{2})^{\alpha-1}} \\
&\quad \times \left[2 + \frac{3}{c\sqrt{1 + (|v_{-}|^2/(4(c^2 - |v_{-}|^2)))}} \frac{d\beta_1 2^{\alpha+3}}{\alpha (|v_{-}|/\sqrt{2} - r) (1 + |x_{-}|/\sqrt{2})^{\alpha}} \right] \\
&\quad \times \|f_1 - f_2\|_T.
\end{aligned} \tag{5.31}$$

Using (5.14), (4.10), and (5.17) we obtain (2.8a). Using (5.14), (4.11), and (5.31) we obtain (2.8b).

Lemma 2.1 is proved.

Proof of Lemma 2.2: The estimates (2.10) and (2.11) follow immediately from (5.3), (4.6), and (5.4a). From (4.1), (4.14), and (4.7) it follows that

$$\int_{-\infty}^{+\infty} F(v_{-s} + x_{-} + f(s)) ds$$

converges absolutely for any $f \in M_{T,r}$. Moreover, using (4.4) and (4.16) and then (4.1), (4.14), and (4.8) we obtain for $u > 0$,

$$\begin{aligned}
& \int_u^{+\infty} \left| g\left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_- + f(s))ds\right) - g\left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_- + f(s))ds\right) \right| d\tau \\
& \leq \frac{d\beta_1 2^{\alpha+1}}{\sqrt{1 + \frac{|v_-|^2}{4(c^2 - |v_-|^2)}}} \int_u^{+\infty} \int_{\tau}^{+\infty} (1 + |x_-|/\sqrt{2} + (|v_-|/\sqrt{2} - r)s)^{-(\alpha+1)} ds d\tau \\
& \leq \frac{d\beta_1 2^{\alpha+1} (1 + |x_-|/\sqrt{2} + (|v_-|/\sqrt{2} - r)u)^{-(\alpha-1)}}{\sqrt{1 + \frac{|v_-|^2}{4(c^2 - |v_-|^2)}}} \alpha(\alpha - 1)(|v_-|/\sqrt{2} - r)^2
\end{aligned} \tag{5.32}$$

As a consequence we can write

$$\begin{aligned}
A_{v_-x_-}(f)(t) = & t \left[g\left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_- + f(s))ds\right) - v_- \right] + \int_{-\infty}^0 \left[g\left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_- \right. \right. \\
& \left. \left. + f(s))ds\right) - v_- \right] d\tau + \int_0^{+\infty} \left[g\left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_- + f(s))ds\right) - g\left(\gamma(v_-) \right. \right. \\
& \left. \left. + \int_{-\infty}^{+\infty} F(v_-s + x_- + f(s))ds\right) \right] d\tau - \int_t^{+\infty} \left[g\left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_- + f(s))ds\right) \right. \\
& \left. - g\left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_- + f(s))ds\right) \right] d\tau
\end{aligned} \tag{5.33}$$

and (2.12) and (2.13) follow, where

$$\begin{aligned}
H_{v_-x_-}(f)(t) = & \int_t^{+\infty} \left[g\left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_- + f(s))ds\right) \right. \\
& \left. - g\left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_- + f(s))ds\right) \right] d\tau.
\end{aligned} \tag{5.34}$$

The formulas (5.34) and (5.32) prove (2.16). Using (5.34), (4.4), (4.16), (4.1), (4.14), and (4.6), we obtain (2.15).

Using (2.13a), (4.4), (4.16), (4.1), (4.14), and (4.7) we obtain (2.14a).

We write

$$\begin{aligned}
l_{v_-x_-}(f) = & A_{v_-x_-}(f)(0) + \int_0^{+\infty} \left[g\left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_- + f(s))ds\right) \right. \\
& \left. - g\left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_- + f(s))ds\right) \right] d\tau.
\end{aligned} \tag{5.35}$$

Using (5.35), (5.7), and (5.32), we obtain (2.14b).

Thus Lemma 2.2 is proved.

Proof of Lemma 2.3: Using (2.3) and (2.7b) we obtain

$$\|y_- - 0\|_T = \|y_-\|_T \leq \rho(c, d, \beta_1, \alpha, |v_-|, |x_-|, r), \quad T = +\infty.$$

Using (2.13a) and (5.10) with (5.14) and (4.11) ($T = +\infty$ and $t \rightarrow +\infty$), we obtain (2.17a).

From (5.35) it follows that

$$\begin{aligned}
 & |l_{v_-,x_-}(y_-) - l_{v_-,x_-}(0)| \\
 & \leq |A_{v_-,x_-}(y_-)(0) - A_{v_-,x_-}(0)(0)| \\
 & + \left| \lim_{t \rightarrow +\infty} \left\{ \int_0^t \left[g \left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_- + y_-(s)) ds \right) - g \left(\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_- + y_-(s)) ds \right) \right. \right. \\
 & - g \left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_-) ds \right) + g \left(\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_-) ds \right) \\
 & \left. \left. - \left(g \left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_- + y_-(s)) ds \right) - g \left(\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_- + y_-(s)) ds \right) \right) \right. \right. \\
 & \left. \left. + \left(g \left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_-) ds \right) - g \left(\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_-) ds \right) \right) \right] d\tau \right\} \right|. \tag{5.36}
 \end{aligned}$$

Using (4.4), (4.16), (4.1), (4.14), and (4.6) we obtain

$$t \left| g \left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_- + f(s)) ds \right) - g \left(\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_- + f(s)) ds \right) \right| \rightarrow 0 \text{ as } t \rightarrow +\infty \tag{5.37}$$

for $f \in M_{T,r}$.

From (5.36) and (5.37) it follows that

$$\begin{aligned}
 & |l_{v_-,x_-}(y_-) - l_{v_-,x_-}(0)| \\
 & \leq |A_{v_-,x_-}(y_-)(0) - A_{v_-,x_-}(0)(0)| \\
 & + \left| \lim_{t \rightarrow +\infty} \left\{ \int_0^t \left[g \left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_- + y_-(s)) ds \right) - g \left(\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_- + y_-(s)) ds \right) \right. \right. \\
 & \left. \left. - g \left(\gamma(v_-) + \int_{-\infty}^{\tau} F(v_-s + x_-) ds \right) + g \left(\gamma(v_-) + \int_{-\infty}^t F(v_-s + x_-) ds \right) \right] d\tau \right\} \right|. \tag{5.38}
 \end{aligned}$$

Using (5.19)–(5.21), (5.24), and (5.30), $\|y_-\|_T \leq \rho(c, d, \beta_1, \alpha, |v_-|, |x_-|, r)$, $T = +\infty$, and (5.38) we obtain (2.17c).

We shall prove (2.17b). First

$$v_- + k_{v_-,x_-}(y_-) = g \left(\gamma(v_-) + \int_{-\infty}^{+\infty} F(v_-s + x_- + y_-(s)) ds \right). \tag{5.39}$$

Using the integral of motion E , we have $|v_-| = |v_- + k_{v_-,x_-}(y_-)|$ and applying γ to (5.39) we obtain

$$\frac{k_{v_-,x_-}(y_-)}{\sqrt{1 - |v_-|^2/c^2}} = \int_{-\infty}^{+\infty} F(v_-s + x_- + y_-(s)) ds. \tag{5.40}$$

From (5.40), (5.12), (5.13), and (4.11) and $\|y_-\|_T \leq \rho(c, d, \beta_1, \alpha, |v_-|, |x_-|, r)$, $T = +\infty$, we obtain (2.17b).

Lemma 2.3 is proved.

VI. PROOFS OF THEOREM 3.2 AND PROPOSITION 1.1

Let $(\theta, x) \in T\mathbb{S}^{d-1}$, $\alpha, d, c, \beta_1, \beta_2$ be fixed.

We shall use

$$\left| \frac{1}{s} \int_{-\infty}^u F(x + \tau\theta) d\tau \right| \leq \frac{\beta_1 \sqrt{d}}{\alpha(s/\sqrt{2})(1 + |x|/\sqrt{2})^\alpha} \quad (6.1a)$$

for $s \in]0, c[$ and $u \in]-\infty, 0]$; replacing θ by $-\theta$ in (6.1a), we obtain

$$\left| \frac{1}{s} \int_u^{+\infty} F(x + \tau\theta) d\tau \right| \leq \frac{\beta_1 \sqrt{d}}{\alpha(s/\sqrt{2})(1 + |x|/\sqrt{2})^\alpha} \quad (6.1b)$$

for $s \in]0, c[$ and $u \in [0, +\infty[$.

We prove (6.1a). As $\theta x = 0$, the following formula is valid:

$$|x + w\theta| \geq |x|/\sqrt{2} + |w|/\sqrt{2}, \quad (6.2)$$

for any $w \in \mathbb{R}$. Then estimate (6.1a) follows from (4.1), (6.2), and (4.6).

Before proving Theorem 3.2, we need to introduce three lemmas and prove them.

Lemma 6.1: There exists integrable $\tilde{g}_{c,d,\beta_0,\beta_1,\alpha,|x|}:]-\infty, 0] \rightarrow [0, +\infty[$ such that

$$\left| (1 + \delta_1(c, \theta, x, s, u))^{-1/2} - 1 - \frac{V(x + u\theta) \sqrt{1 - \frac{s^2}{c^2}}}{c^2} \right| \leq \tilde{g}_{c,d,\beta_0,\beta_1,\alpha,|x|}(u)(1 - s^2/c^2), \quad (6.3)$$

for $u \in]-\infty, 0]$ and $s < c$, $s \geq z_2(c, d, \beta_1, \alpha, |x|)$, and where

$$\delta_1(c, \theta, x, s, u) = \frac{-2V(x + u\theta) \sqrt{1 - \frac{s^2}{c^2}} + \left(\frac{1}{s^2} - \frac{1}{c^2} \right) \left| \int_{-\infty}^u F(x + \tau\theta) d\tau \right|^2}{c^2} \geq -\frac{3}{4}, \quad (6.4)$$

for $u \in]-\infty, 0]$ and $s < c$, $s \geq z_2(c, d, \beta_1, \alpha, |x|)$.

Proof of Lemma 6.1.

Let $s \in]0, c[$, $s \geq z_2(c, d, \beta_1, \alpha, |x|)$ and $u \in]-\infty, 0]$.

From (6.1a) and the definition of $z_2(c, d, \beta_1, \alpha, |x|)$ [see (1.7d)] it follows that

$$\left| \frac{s\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s} \int_{-\infty}^u F(x + \tau\theta) d\tau \right| \geq \frac{s}{2\sqrt{1 - s^2/c^2}}. \quad (6.5)$$

Expanding the square of the norm we obtain

$$\left| \frac{s\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s} \int_{-\infty}^u F(x + \tau\theta) d\tau \right|^2 = \frac{s^2}{1 - s^2/c^2} - \frac{2V(x + u\theta)}{\sqrt{1 - s^2/c^2}} + \left| \frac{1}{s} \int_{-\infty}^u F(x + \tau\theta) d\tau \right|^2. \quad (6.6)$$

Using (6.5) and (6.6), we obtain

$$\delta_1(c, \theta, x, s, u) = \frac{1 + \frac{1}{c^2} \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^u F(x + \tau\theta) d\tau \right|^2}{1 + \frac{s^2}{c^2 - s^2}} - 1 \geq \frac{1 + \frac{s^2}{4(c^2 - s^2)}}{1 + \frac{s^2}{c^2 - s^2}} - 1 \geq -3/4. \tag{6.7}$$

Moreover, from the definition of $\delta_1(c, \theta, x, s, u)$, (1.2) and (6.1a) and the hypothesis $s \geq z_2(c, d, \beta_1, \alpha, |x|)$, $s < c$, it follows that

$$|\delta_1(c, \theta, x, s, u)| \leq \sqrt{1 - s^2/c^2} \left[\frac{\beta_0 2(1 + |x|/\sqrt{2} - u/\sqrt{2})^{-\alpha}}{c^2} + \frac{\sqrt{1 - z_2(c, d, \beta_1, \alpha, |x|)^2/c^2} \beta_1^2 d 2(1 + |x|/\sqrt{2} - u/\sqrt{2})^{-2\alpha}}{z_2(c, d, \beta_1, \alpha, |x|)^2 c^2 \alpha^2} \right]. \tag{6.8}$$

Using Taylor expansion of the map $] -1, +\infty[\rightarrow \mathbb{R}, \delta \mapsto (1 + \delta)^{-1/2}$ at $\delta=0$, we obtain that

$$(1 + \delta_1(c, \theta, x, s, u))^{-1/2} - 1 - \frac{V(x + u\theta) \sqrt{1 - \frac{s^2}{c^2}}}{c^2} = - \frac{1 - s^2/c^2}{2s^2 c^2} \left| \int_{-\infty}^u F(x + \tau\theta) d\tau \right|^2 + \frac{3}{4} \int_0^1 (1 - w) \times (1 + w \delta_1(c, \theta, x, s, u))^{-5/2} dw \delta_1(c, \theta, x, s, u)^2. \tag{6.9}$$

We estimate the first term on the right-hand side of (6.9) with the help of (6.1a). We estimate the second term on the right-hand side of (6.9) with the help of (6.7) and (6.8). Using also the inequality $s \geq z_2(c, d, \beta_1, \alpha, |x|)$, we finally obtain

$$\left| (1 + \delta_1(c, \theta, x, s, u))^{-1/2} - 1 - \frac{V(x + u\theta) \sqrt{1 - \frac{s^2}{c^2}}}{c^2} \right| \leq \tilde{g}_{c,d,\beta_0,\beta_1,\alpha,|x|}(u),$$

where

$$\tilde{g}_{c,d,\beta_0,\beta_1,\alpha,|x|}(u) = \frac{d\beta_1^2}{c^2 z_2(c, d, \beta_1, \alpha, |x|)^2 \alpha^2 (1 + |x|/\sqrt{2} - u/\sqrt{2})^{2\alpha}} + 4^{5/2} \frac{3}{2c^4} \left[\beta_0 (1 + |x|/\sqrt{2} - u/\sqrt{2})^{-\alpha} + \frac{\sqrt{1 - z_2(c, d, \beta_1, \alpha, |x|)^2/c^2} \beta_1^2 d (1 + |x|/\sqrt{2} - u/\sqrt{2})^{-2\alpha}}{z_2(c, d, \beta_1, \alpha, |x|)^2 \alpha^2} \right]^2.$$

Lemma 6.1 is proved.

Lemma 6.2: Let $\beta > 0$, $s \in]0, c[$, $s \geq z_2(c, d, \beta_1, \alpha, |x|)$. Then there exists a positive real number $k_{\beta,c,d,\beta_1,\alpha,|x|}$ such that

$$\left| \left(1 + \frac{1 - s^2/c^2}{s^2 c^2} \left| \int_{-\infty}^{+\infty} F(x + \tau\theta) d\tau \right|^2 \right)^{-\beta} - 1 \right| \leq (1 - s^2/c^2) k_{\beta,c,d,\beta_1,\alpha,|x|}.$$

Proof of Lemma 6.2: We define

$$\delta_2(c, \theta, x, s) = \frac{1 - s^2/c^2}{s^2 c^2} \left| \int_{-\infty}^{+\infty} F(x + \tau\theta) d\tau \right|^2 \geq 0. \tag{6.10}$$

Using (6.1) and $s \geq z_2(c, d, \beta_1, \alpha, |x|)$, we obtain

$$\delta_2(c, \theta, x, s) \leq (1 - s^2/c^2) \frac{d\beta_1^2 8}{c^2 z_2(c, d, \beta_1, \alpha, |x|)^2 \alpha^2 (1 + |x|/\sqrt{2})^{2\alpha}}. \tag{6.11}$$

Using the Taylor expansion of the map $]-1, +\infty[\rightarrow \mathbb{R}, \delta \mapsto (1 + \delta)^{-\beta}$ at $\delta=0$ and using (6.10), we obtain

$$(1 + \delta_2(c, \theta, x, s))^{-\beta} - 1 = -\beta \delta_2(c, \theta, x, s) \int_0^1 (1 + w \delta_2(c, \theta, x, s))^{-(\beta+1)} dw. \tag{6.12}$$

From (6.10)–(6.12) it follows that

$$|(1 + \delta_2(c, \theta, x, s))^{-\beta} - 1| \leq \beta \delta_2(c, \theta, x, s) \leq (1 - s^2/c^2) k_{\beta, c, d, \beta_1, \alpha, |x|},$$

where

$$k_{\beta, c, d, \beta_1, \alpha, |x|} = \frac{\beta d \beta_1^2 8}{c^2 z_2(c, d, \beta_1, \alpha, |x|)^2 \alpha^2 (1 + |x|/\sqrt{2})^{2\alpha}}.$$

Lemma 6.2 is proved.

We always suppose that $(\theta, x) \in T\mathbb{S}^{d-1}$, $\alpha, d, c, \beta_1, \beta_2$ are fixed. Let $s \in]0, c[, s \geq z_2(c, d, \beta_1, \alpha, |x|), u \in [0, +\infty[$, we define

$$A(c, \theta, x, s, u) = (1 + t(c, \theta, x, s, u))^{-1/2}, \tag{6.13}$$

where

$$t(c, \theta, x, s, u) = \frac{1 + \frac{1}{c^2} \left| \frac{s\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s} \int_{-\infty}^u F(x + \tau\theta) d\tau \right|^2}{1 + \frac{1}{c^2} \left| \frac{s\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(x + \tau\theta) d\tau \right|^2} - 1. \tag{6.14}$$

Expanding the square of the norms in the numerator and denominator of the fraction of the right-hand side of (6.14), we obtain that

$$t(c, \theta, x, s, u) = \frac{-2V(x + u\theta)\sqrt{1 - s^2/c^2} + \frac{1 - s^2/c^2}{s^2} \left| \int_u^{+\infty} F(x + \tau\theta) d\tau \right|^2}{\left(1 + \frac{(1 - s^2/c^2)}{s^2 c^2} \left| \int_{-\infty}^{+\infty} F(x + \tau\theta) d\tau \right|^2 \right) c^2} - \frac{\frac{2(1 - s^2/c^2)}{s^2} \int_u^{+\infty} F(x + \tau\theta) d\tau \cdot \int_{-\infty}^{+\infty} F(x + \tau\theta) d\tau}{\left(1 + \frac{(1 - s^2/c^2)}{s^2 c^2} \left| \int_{-\infty}^{+\infty} F(x + \tau\theta) d\tau \right|^2 \right) c^2}. \tag{6.15}$$

Lemma 6.3: There exists $h_{c, d, \beta_0, \beta_1, \alpha, |x|}: [0, +\infty[\rightarrow [0, +\infty[$ an integrable function such that for $s \in]0, c[, s \geq z_2(c, d, \beta_1, \alpha, |x|), u \in [0, +\infty[$,

$$\left| A(c, \theta, x, s, u) - 1 - V(x + u\theta) \frac{\sqrt{1 - s^2/c^2}}{c^2} \right| \leq (1 - s^2/c^2) h_{c, d, \beta_0, \beta_1, \alpha, |x|}(u).$$

Proof of Lemma 6.3: We first look for a lower bound for $t(c, \theta, x, s, u)$. The following estimate is valid

$$\left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^u F(x+\tau\theta) d\tau \right| \geq \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(x+\tau\theta) d\tau \right| - \left| \frac{1}{s} \int_u^{+\infty} F(x+\tau\theta) d\tau \right|. \quad (6.16)$$

From (6.1) it follows that

$$\left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(x+\tau\theta) d\tau \right| \geq \frac{s}{\sqrt{1-s^2/c^2}} - \frac{2\beta_1\sqrt{d}}{\alpha(s/\sqrt{2})(1+|x|/\sqrt{2})^\alpha}. \quad (6.17)$$

Using first (6.1b) and then $s \geq z_2(c, d, \beta_1, \alpha, |x|)$ and (6.17) we obtain

$$\begin{aligned} \left| \frac{1}{s} \int_u^{+\infty} F(x+\tau\theta) d\tau \right| &\leq \frac{\beta_1\sqrt{d}}{(s/\sqrt{2})\alpha(1+|x|/\sqrt{2})^\alpha} \leq \frac{1}{6} \left(\frac{s}{\sqrt{1-s^2/c^2}} - \frac{2\beta_1\sqrt{d}}{\alpha(s/\sqrt{2})(1+|x|/\sqrt{2})^\alpha} \right) \\ &\leq \frac{1}{6} \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(x+\tau\theta) d\tau \right|. \end{aligned} \quad (6.18)$$

From (6.16) and (6.18) it follows that

$$\left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^u F(x+\tau\theta) d\tau \right| \geq \frac{5}{6} \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(x+\tau\theta) d\tau \right|. \quad (6.19)$$

Using (6.14) and (6.19) we obtain

$$t(c, \theta, x, s, u) \geq \frac{25}{36} - 1 = -\frac{11}{36}. \quad (6.20)$$

Now we look for an upper bound for $t(c, \theta, x, s, u)$. The right-hand side of (6.15) consists of a subtraction of two fractions whose denominator is greater than c^2 and this implies

$$\begin{aligned} |t(c, \theta, x, s, u)| &\leq c^{-2} \left| -2V(x+u)\sqrt{1-s^2/c^2} + \frac{1-s^2/c^2}{s^2} \left| \int_u^{+\infty} F(x+\tau\theta) d\tau \right|^2 \right. \\ &\quad \left. - \frac{2(1-s^2/c^2)}{s^2} \int_u^{+\infty} F(x+\tau\theta) d\tau \star \int_{-\infty}^{+\infty} F(x+\tau\theta) d\tau \right|, \end{aligned} \quad (6.21)$$

where \star denotes the usual scalar product on \mathbb{R}^d . Thus, using (1.2), (6.1), (4.7) and the fact that $s \geq z_2(c, d, \beta_1, \alpha, |x|)$, we obtain

$$\begin{aligned} |t(c, \theta, x, s, u)| &\leq c^{-2} \sqrt{1-s^2/c^2} \left[2\beta_0(1+|x|/\sqrt{2}+u/\sqrt{2})^{-\alpha} \right. \\ &\quad + \frac{\sqrt{1-z_2(c, d, \beta_1, \alpha, |x|)^2/c^2}}{z_2(c, d, \beta_1, \alpha, |x|)^2} \frac{d\beta_1^2 2}{\alpha^2(1+|x|/\sqrt{2}+u/\sqrt{2})^{2\alpha}} \\ &\quad \left. + \frac{\sqrt{1-z_2(c, d, \beta_1, \alpha, |x|)^2/c^2}}{z_2(c, d, \beta_1, \alpha, |x|)^2} \frac{d\beta_1^2 8}{\alpha^2(1+|x|/\sqrt{2}+u/\sqrt{2})^\alpha(1+|x|/\sqrt{2})^\alpha} \right]. \end{aligned} \quad (6.22)$$

Using (6.13) and (6.20), the Taylor expansion of the map $]-1, +\infty[\mapsto \mathbb{R}$, $\delta \mapsto (1+\delta)^{-1/2}$ at $\delta=0$ and (6.15), we obtain

$$\begin{aligned}
& \left| A(c, \theta, x, s, u) - 1 - \frac{V(x + u\theta)\sqrt{1 - s^2/c^2}}{c^2} \right| \\
&= \left| \frac{1}{2} t(c, \theta, x, s, u) + \frac{3}{4} \int_0^1 (1-w)(1 + wt(c, \theta, x, s, u))^{-5/2} dw t(c, \theta, x, s, u)^2 \right. \\
&\quad \left. - \frac{V(x + u\theta)\sqrt{1 - s^2/c^2}}{c^2} \right| \\
&\leq \left| \frac{V(x + u\theta)\sqrt{1 - s^2/c^2}}{c^2} \left[1 - \left(1 + \frac{1 - s^2/c^2}{c^2 s^2} \left| \int_{-\infty}^{+\infty} F(x + \tau\theta) d\tau \right|^2 \right)^{-1} \right] \right| \\
&\quad + \frac{1}{2} \frac{\frac{1 - s^2/c^2}{s^2} \left| \int_u^{+\infty} F(x + \tau\theta) d\tau \right|^2 + \frac{2(1 - s^2/c^2)}{s^2} \int_u^{+\infty} |F(x + \tau\theta)| d\tau \int_{-\infty}^{+\infty} |F(x + \tau\theta)| d\tau}{\left(1 + \frac{(1 - s^2/c^2)}{s^2 c^2} \left| \int_{-\infty}^{+\infty} F(x + \tau\theta) d\tau \right|^2 \right) c^2} \\
&\quad + \frac{3}{8} \left(\frac{25}{36} \right)^{-5/2} t(c, \theta, x, s, u)^2. \tag{6.23}
\end{aligned}$$

We use Lemma 6.2, conditions (1.2) and the fact that $s \geq z_2(c, d, \beta_1, \alpha, |x|)$ to estimate the first term on the right-hand side of the inequality (6.23). In order to estimate the second term on the right-hand side of the inequality (6.23), we use the fact that the denominator is greater than c^2 , and we also use (6.1), (4.7), the fact that $s \geq z_2(c, d, \beta_1, \alpha, |x|)$. We estimate the third term on the right-hand side of the inequality with (6.22). Thus we obtain

$$\left| A(c, \theta, x, s, u) - 1 - \frac{V(x + u\theta)\sqrt{1 - s^2/c^2}}{c^2} \right| \leq (1 - s^2/c^2) h_{c, d, \beta_0, \beta_1, \alpha, |x|}(u),$$

where

$$\begin{aligned}
h_{c, d, \beta_0, \beta_1, \alpha, |x|}(u) &= \frac{1}{c^2} (1 + |x|/\sqrt{2} + u/\sqrt{2})^{-\alpha} \left\{ \beta_0 k_{1, c, d, \beta_1, \alpha, |x|} \sqrt{1 - z_2(c, d, \beta_1, \alpha, |x|)^2/c^2} \right. \\
&\quad + \frac{\beta_1^2 d}{\alpha^2 z_2(c, d, \beta_1, \alpha, |x|)^2} ((1 + |x|/\sqrt{2} + u/\sqrt{2})^{-\alpha} + 4(1 + |x|/\sqrt{2})^{-\alpha}) \\
&\quad + \frac{3}{2c^2} \left(\frac{25}{36} \right)^{-5/2} \left[\beta_0 (1 + |x|/\sqrt{2} + u/\sqrt{2})^{-\alpha/2} \right. \\
&\quad + \frac{d\beta_1^2 \sqrt{1 - z_2(c, d, \beta_1, \alpha, |x|)^2/c^2}}{z_2(c, d, \beta_1, \alpha, |x|)^2 \alpha^2 (1 + |x|/\sqrt{2} + u/\sqrt{2})^{\alpha/2}} \\
&\quad \left. \left. \times ((1 + |x|/\sqrt{2} + u/\sqrt{2})^{-\alpha} + 4(1 + |x|/\sqrt{2})^{-\alpha}) \right]^2 \right\}.
\end{aligned}$$

Lemma 6.3 is proved.

Proof of Theorem 3.2: Let $(\theta, x) \in T\mathbb{S}^{d-1}$, $\alpha, d, c, \beta_1, \beta_2, s \in]0, c[$, $s \geq z_2(c, d, \beta_1, \alpha, |x|)$ be fixed. We shall study the asymptotics of $l_{s, \theta, x}(0)$ which is defined by formula (2.13b).

First we look for the asymptotics of

$$\int_{-\infty}^0 \left[g \left(\gamma(s\theta) + \int_{-\infty}^{\tau} F(us\theta + x) du \right) - s\theta \right] d\tau.$$

By changes of variables, we obtain

$$\begin{aligned} & \int_{-\infty}^0 \left[g \left(\gamma(s\theta) + \int_{-\infty}^{\tau} F(us\theta + x) du \right) - s\theta \right] d\tau \\ &= \int_{-\infty}^0 \left[\frac{\frac{\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s^2} \int_{-\infty}^{\tau} F(u\theta + x) du}{\sqrt{1+c^{-2}} \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{\tau} F(u\theta + x) du \right|^2} - \theta \right] d\tau. \end{aligned} \tag{6.24}$$

Expanding the square of the norm in the denominator of the fraction under the integral in (6.24), the denominator becomes

$$\left(1 + c^{-2} \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{\tau} F(u\theta + x) du \right|^2 \right)^{-1/2} = (1 + \delta_1(c, \theta, x, s, \tau))^{-1/2} (1 - s^2/c^2)^{1/2}, \tag{6.25}$$

where δ_1 is defined by formula (6.4). We define

$$\begin{aligned} \Lambda_1(\theta, x, s) &= \left| (1 - s^2/c^2)^{-1/2} \int_{-\infty}^0 \left[g \left(\gamma(s\theta) + \int_{-\infty}^{\tau} F(us\theta + x) du \right) - s\theta \right] d\tau - c^{-2} \int_{-\infty}^0 V(\tau\theta + x) d\tau \theta \right. \\ &\quad \left. - s^{-2} \int_{-\infty}^0 \int_{-\infty}^{\tau} F(u\theta + x) du d\tau \right|. \end{aligned} \tag{6.26}$$

From (6.26), (6.24), and (6.25), it follows that

$$\begin{aligned} \Lambda_1(\theta, x, s) &\leq \int_{-\infty}^0 \left| (1 + \delta_1(c, \theta, x, s, \tau))^{-1/2} - 1 - c^{-2} V(\tau\theta + x) \sqrt{1 - s^2/c^2} \right| \\ &\quad \times \left(\frac{1}{\sqrt{1 - s^2/c^2}} + s^{-2} \int_{-\infty}^{\tau} |F(u\theta + x)| du \right) d\tau \\ &\quad + \int_{-\infty}^0 \left| (1 + c^{-2} V(\tau\theta + x) \sqrt{1 - s^2/c^2}) \left(\frac{\theta}{\sqrt{1 - s^2/c^2}} + s^{-2} \int_{-\infty}^{\tau} F(u\theta + x) du \right) \right. \\ &\quad \left. - \frac{\theta}{\sqrt{1 - s^2/c^2}} - c^{-2} V(\tau\theta + x) \theta - s^{-2} \int_{-\infty}^{\tau} F(u\theta + x) du \right| d\tau. \end{aligned} \tag{6.27}$$

We estimate the first integral on the right-hand side of (6.27) by the use of Lemma 6.1. Therefore expanding the first product under the second integral of the form $\int_{-\infty}^0$ on the right-hand side of (6.27), we obtain

$$\begin{aligned} \Lambda_1(\theta, x, s) &\leq \sqrt{1 - s^2/c^2} \int_{-\infty}^0 \left[\tilde{g}_{c,d,\beta_0,\beta_1,\alpha,|x|}(\tau) \left(1 + s^{-2} \sqrt{1 - s^2/c^2} \int_{-\infty}^{\tau} |F(u\theta + x)| du \right) \right. \\ &\quad \left. + \left| \frac{V(\tau\theta + x)}{s^2 c^2} \int_{-\infty}^{\tau} F(u\theta + x) du \right| \right] d\tau. \end{aligned} \tag{6.28}$$

We define $|V|_{\infty} = \sup_{y \in \mathbb{R}^d} |V(y)|$. Using (6.28), (1.2), (6.1a), and (4.8) and the fact that $s \geq z_2(c, d, \beta_1, \alpha, |x|)$, we obtain

$$\Lambda_1(\theta, x, s) \leq \sqrt{1-s^2/c^2} \left[\left(1 + \frac{\sqrt{1-z_2(c, d, \beta_1, \alpha, |x|)^2/c^2}}{z_2(c, d, \beta_1, \alpha, |x|)^2} \frac{\beta_1 \sqrt{d} \sqrt{2}}{\alpha(1+|x|/\sqrt{2})^\alpha} \right) \int_{-\infty}^0 \bar{g}_{c, d, \beta_0, \beta_1, \alpha, |x|}(\tau) d\tau \right. \\ \left. + \frac{\beta_1 \sqrt{d} |V|_\infty}{z_2(c, d, \beta_1, \alpha, |x|)^2 c^2 \alpha (\alpha-1) (1+|x|/\sqrt{2})^{\alpha-1}} \right]. \quad (6.29)$$

Now we look for the asymptotics of

$$\int_0^{+\infty} \left[g \left(\gamma(s\theta) + \int_{-\infty}^{\tau} F(us\theta+x) du \right) - g \left(\gamma(s\theta) + \int_{-\infty}^{+\infty} F(us\theta+x) du \right) \right] d\tau.$$

By changes of variables, we obtain

$$\int_0^{+\infty} \left[g \left(\gamma(s\theta) + \int_{-\infty}^{\tau} F(us\theta+x) du \right) - g \left(\gamma(s\theta) + \int_{-\infty}^{+\infty} F(us\theta+x) du \right) \right] d\tau \\ = \int_0^{+\infty} \left[\frac{\frac{\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s^2} \int_{-\infty}^{\tau} F(u\theta+x) du}{\sqrt{1+c^{-2}} \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{\tau} F(u\theta+x) du \right|^2} \right. \\ \left. - \frac{\frac{\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s^2} \int_{-\infty}^{+\infty} F(u\theta+x) du}{\sqrt{1+c^{-2}} \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(u\theta+x) du \right|^2} \right] d\tau. \quad (6.30)$$

First we study the denominator of the first fraction under the integral of (6.30). From (6.14) and (6.13) it follows that

$$\left(1 + c^{-2} \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{\tau} F(u\theta+x) du \right|^2 \right)^{-1/2} \\ = \left(1 + c^{-2} \left| \frac{s\theta}{\sqrt{1-s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(u\theta+x) du \right|^2 \right)^{-1/2} A(c, \theta, x, s, \tau). \quad (6.31)$$

We define

$$\Lambda_2(c, \theta, x, s) = \left| (1-s^2/c^2)^{-1/2} \int_0^{+\infty} \left[g \left(\gamma(s\theta) + \int_{\tau}^{+\infty} F(us\theta+x) du \right) \right. \right. \\ \left. \left. - g \left(\gamma(s\theta) + \int_{-\infty}^{+\infty} F(us\theta+x) du \right) \right] d\tau - c^{-2} \int_0^{+\infty} V(\tau\theta+x) d\tau \right. \\ \left. + s^{-2} \int_0^{+\infty} \int_{\tau}^{+\infty} F(u\theta+x) du d\tau \right|. \quad (6.32)$$

From (6.30)–(6.32) it follows that

$$\Lambda_2(c, \theta, x, s) \leq \Lambda_{2,1}(c, \theta, x, s) + \Lambda_{2,2}(c, \theta, x, s), \quad (6.33)$$

where

$$\Lambda_{2,1}(c, \theta, x, s) = \int_0^{+\infty} \left| (1 - s^2/c^2)^{-1/2} \left(1 + \frac{1}{c^2} \left| \frac{s\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(u\theta + x) du \right|^2 \right)^{-1/2} \right. \\ \left. \times \left(A(c, \theta, x, s, \tau) - 1 - V(\tau\theta + x) \frac{\sqrt{1 - s^2/c^2}}{c^2} \right) \left(\frac{\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s^2} \int_{-\infty}^{\tau} F(u\theta + x) du \right) \right| d\tau, \tag{6.34a}$$

$$\Lambda_{2,2}(c, \theta, x, s) = \int_0^{+\infty} \left| (1 - s^2/c^2)^{-1/2} \left(1 + \frac{1}{c^2} \left| \frac{s\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(u\theta + x) du \right|^2 \right)^{-1/2} \right. \\ \times \left[\left(1 + V(\tau\theta + x) \frac{\sqrt{1 - s^2/c^2}}{c^2} \right) \left(\frac{\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s^2} \int_{-\infty}^{\tau} F(u\theta + x) du \right) \right. \\ \left. - \left(\frac{\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s^2} \int_{-\infty}^{+\infty} F(u\theta + x) du \right) \right] \\ \left. - \frac{V(\tau\theta + x)}{c^2} \theta + \frac{1}{s^2} \int_{\tau}^{+\infty} F(u\theta + x) du \right| d\tau. \tag{6.34b}$$

Let us estimate $\Lambda_{2,1}(c, \theta, x, s)$.

From Lemma 6.3 and (6.34a) it follows that

$$\Lambda_{2,1}(c, \theta, x, s) \leq \sqrt{1 - s^2/c^2} \left(1 + \frac{1}{c^2} \left| \frac{s\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(u\theta + x) du \right|^2 \right)^{-1/2} \\ \times \left(\frac{1}{\sqrt{1 - s^2/c^2}} + \frac{1}{s^2} \int_{-\infty}^{+\infty} |F(u\theta + x)| du \right) \int_0^{+\infty} h_{c,d,\beta_0,\beta_1,\alpha,|x|}(\tau) d\tau. \tag{6.35}$$

In addition, expanding the square of the norm, we obtain

$$\left(1 + \frac{1}{c^2} \left| \frac{s\theta}{\sqrt{1 - s^2/c^2}} + \frac{1}{s} \int_{-\infty}^{+\infty} F(u\theta + x) du \right|^2 \right)^{-1/2} \\ = \sqrt{1 - s^2/c^2} \left(1 + \frac{1 - s^2/c^2}{s^2 c^2} \left| \int_{-\infty}^{+\infty} F(u\theta + x) du \right|^2 \right)^{-1/2} \tag{6.36a}$$

$$\leq \sqrt{1 - s^2/c^2}. \tag{6.36b}$$

Using (6.35), (6.36), (4.1), (6.2), and (4.7) and the fact that $s \geq z_2(c, d, \beta_1, \alpha, |x|)$, we obtain

$$\Lambda_{2,1}(c, \theta, x, s) \leq \sqrt{1 - s^2/c^2} \left(1 + \frac{\beta_1 \sqrt{d} \sqrt{1 - z_2(c, d, \beta_1, \alpha, |x|)^2/c^2} 2\sqrt{2}}{z_2(c, d, \beta_1, \alpha, |x|)^2 \alpha (1 + |x|/\sqrt{2})^\alpha} \right) \int_0^{+\infty} h_{c,d,\beta_0,\beta_1,\alpha,|x|}(\tau) d\tau. \tag{6.37}$$

Let us estimate $\Lambda_{2,2}(c, \theta, x, s)$.

From (6.34b) and (6.36a) it follows that

$$\begin{aligned} \Lambda_{2,2}(c, \theta, x, s) &\leq \int_0^{+\infty} \left| \left(1 + \frac{1-s^2/c^2}{s^2 c^2} \right) \left| \int_{-\infty}^{+\infty} F(u\theta+x) du \right|^2 - 1 \right| \\ &\quad \times \left| -\frac{1}{s^2} \int_{\tau}^{+\infty} F(u\theta+x) du + \frac{V(\tau\theta+x)}{c^2} \theta + \frac{\sqrt{1-s^2/c^2}}{s^2 c^2} V(\tau\theta+x) \right. \\ &\quad \left. \times \int_{-\infty}^{\tau} F(u\theta+x) du \right| d\tau + \int_0^{+\infty} \left| \frac{\sqrt{1-s^2/c^2}}{s^2 c^2} V(\tau\theta+x) \int_{-\infty}^{\tau} F(u\theta+x) du \right| d\tau. \end{aligned} \tag{6.38}$$

Thus using Lemma 6.2, conditions (1.2), (4.1), (6.2), (4.6), and (4.7) and the fact that $s \geq z_2(c, d, \beta_1, \alpha, |x|)$, it follows that

$$\begin{aligned} \Lambda_{2,2}(c, \theta, x, s) &\leq \sqrt{1-s^2/c^2} \left[\frac{k_{1/2,c,d,\beta_1,\alpha,|x|} \sqrt{1-z_2(c,d,\beta_1,\alpha,|x|)^2/c^2}}{(\alpha-1)(1+|x|/\sqrt{2})^{\alpha-1}} \right. \\ &\quad \times \left(\frac{\sqrt{d}\beta_1 2}{z_2(c,d,\beta_1,\alpha,|x|)^2 \alpha} + \frac{\beta_0 \sqrt{2}}{c^2} + \frac{\sqrt{d}\beta_0 \beta_1 4 \sqrt{1-z_2(c,d,\beta_1,\alpha,|x|)^2/c^2}}{z_2(c,d,\beta_1,\alpha,|x|)^2 c^2 \alpha (1+|x|/\sqrt{2})^\alpha} \right) \\ &\quad \left. + \frac{\sqrt{d}\beta_0 \beta_1 4}{z_2(c,d,\beta_1,\alpha,|x|)^2 c^2 \alpha (\alpha-1)(1+|x|/\sqrt{2})^{2\alpha-1}} \right]. \end{aligned} \tag{6.39}$$

From (2.13b), (6.26), (6.29), (6.32), (6.34), (6.35), and (6.39) it follows that there exists $C_{c,d,\beta_0,\beta_1,\alpha,|x|}$ such that

$$\begin{aligned} &\left| \frac{l_{s\theta,x}(0)}{\sqrt{1-s^2/c^2}} - \frac{1}{c^2} PV(\theta,x) \theta + \frac{1}{s^2} \int_0^{+\infty} \int_{\tau}^{+\infty} F(x+u\theta) du d\tau - \frac{1}{s^2} \int_{-\infty}^0 \int_{-\infty}^{\tau} F(x+u\theta) du d\tau \right| \\ &\leq \Lambda_1(c, \theta, x, s) + \Lambda_2(c, \theta, x, s) \leq C_{c,d,\beta_0,\beta_1,\alpha,|x|} \sqrt{1-s^2/c^2}. \end{aligned} \tag{6.40}$$

The estimate (3.9) follows from (6.40).

Theorem 3.2 is proved.

Proof of Proposition 1.1: The item (1) follows immediately from

$$\frac{d}{dt} V(t\theta+x) = \nabla V(t\theta+x) \theta \quad \text{for all } (\theta,x) \in TS^{d-1}, \quad t \in \mathbb{R}.$$

Proof of item (2). Take

$$V(x) = \frac{x_1}{(1+|x|^2)^\beta} \quad \text{for } x = (x_1, \dots, x_d) \in \mathbb{R}^d, \beta > 1.$$

and take $(\theta,x) \in TS^{d-1}$. By a straightforward calculation and using $\theta x=0$, we obtain

$$\begin{aligned} &\left(\int_{-\infty}^0 \int_{-\infty}^{\tau} F(s\theta+x) ds d\tau - \int_0^{+\infty} \int_{\tau}^{+\infty} F(s\theta+x) ds d\tau + PV(\theta,x) \theta \right) \star x \\ &= -4\beta\theta_1 |x|^2 \int_0^{+\infty} \int_{\tau}^{+\infty} \frac{s}{(1+s^2+|x|^2)^{\beta+1}} ds d\tau \neq 0 \text{ if and only if } x \neq 0 \text{ and } \theta_1 \neq 0, \end{aligned}$$

where \star denotes the scalar product.

Proof of item (3): Let V be a spherical symmetric potential [i.e., V takes the form $m(|x|)$] that satisfies the conditions (1.2) [e.g., $V(x)=(1+|x|^2)^{-\beta}$ where $\beta > \frac{1}{2}$]. Then $m \in C^1(]0, +\infty[, \mathbb{R})$ and

$\nabla V(x) = m'(|x|)(x/|x|)$. Let $(\theta, x) \in TS^{d-1}$ and let θ^\perp be an orthogonal vector to θ . A straightforward calculation gives

$$F(s\theta + x)\theta^\perp = m'(\sqrt{s^2 + |x|^2}) \frac{x \star \theta^\perp}{\sqrt{s^2 + |x|^2}}$$

for any $s \in \mathbb{R}$. Hence

$$\left(\int_{-\infty}^0 \int_{-\infty}^{\tau} F(s\theta + x) ds d\tau - \int_0^{+\infty} \int_{\tau}^{+\infty} F(s\theta + x) ds d\tau + PV(\theta, x)\theta \right) \star \theta^\perp = 0. \quad (6.41)$$

Item (3) follows from item (1) and formula (6.41).

Proposition 1.1 is proved.

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