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Autor(en): **Graf, Gian Michele**

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A remark on long-range Stark scattering

Gian Michele Graf*

Division of Physics, Mathematics, and Astronomy
California Institute of Technology
Pasadena, CA 91125

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Abstract. We propose a modified wave operator for long-range scattering in presence of an accelerating force. Its relevance in connection with classical scattering is addressed.

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Introduction

The wave operators for the pair (H, H_0) of Stark Hamiltonians with $H = H_0 + V$ and

$$H_0 = \frac{p^2}{2} - g \cdot x, \quad 0 \neq g \in \mathbf{R}^\nu$$

on $\mathcal{H} = L^2(\mathbf{R}^\nu)$ do not exist [6] if $V = V(x)$ behaves as $|x|^{-\varepsilon}$, $\varepsilon \leq 1/2$ as $x \rightarrow \infty$. Recently, several proposals [3, 5, 8] for modified wave operators dealing with slowly decaying potentials were made. Here we add one more, based on a simple Dollard type argument: The classical free Stark trajectories $x(t) = gt^2/2 + p_0t + x_0$ suggest that $e^{-itH_0}e^{-i\Phi(t)}$ with

$$\Phi(t) := \int_0^t V(gs^2/2) ds$$

is a candidate for a comparison dynamics.

Theorem 1. *Let $V \in C^1(\mathbf{R}^\nu)$ be real-valued with*

$$|\nabla V(x)| \leq C(1 + |x|)^{-(1+\varepsilon)} \quad (1)$$

for some $C, \varepsilon > 0$. Then the wave operator

$$\Omega := s\text{-}\lim_{t \rightarrow \infty} e^{itH} e^{-itH_0} e^{-i\Phi(t)} \quad (2)$$

exists and is unitary.

The reason for stating this result comes from [6]. There a discrepancy between the quantum and the classical scattering problem was discovered, as for in the latter one the wave operators exist and are complete without modification basically as long as $V(x) = O(|x|^{-\varepsilon})$ for some $\varepsilon > 0$. We believe our result heals this discrepancy for the class of potentials we consider, since the comparison dynamics differs multiplicatively from the free Stark one only by a phase, which is physically irrelevant. Actually, no modification at all is needed if the asymptotic condition is formulated in the Heisenberg picture: The above result then implies that

$$\mu(A) := s\text{-}\lim_{t \rightarrow \infty} e^{itH} e^{-itH_0} A e^{itH_0} e^{-itH}$$

exists and is an automorphism on $\mathcal{L}(\mathcal{H})$. By contrast, this limit typically exists in long-range scattering only for $A \in \{H_0\}'$, the von Neumann algebra of operators commuting with bounded functions of H_0 [1]. In this respect (1) behaves as a short-range potential.

It follows from (1) that $\lim_{x \rightarrow \infty} V(x)$ exists. We may assume this limit to be zero, since (2) is not affected if the potential is shifted by a constant. Then $|V(x)| \leq C(1 + |x|)^{-\varepsilon}$, which is assumed also by [3, 5, 8]. However there stronger oscillations of the potential are allowed, since (1) is replaced by a weaker decay.

Remark. The hypothesis (1) can be weakened logarithmically [6].

Proofs

Let us state some kinematical remarks beforehand. The following propagation estimate for the free dynamics without electric field is well-known (see e.g. [4], Lemma 6.3): Let $f \in C_0^\infty(\mathbf{R}^\nu)$ with $f(y) = 0$ for $|y| \geq 1$, and let $\alpha > 1$. Then for $R > 0, t \geq 0$ and any $N > 0$

$$\|F(|x| > \alpha(R + t))e^{-itp^2/2} f(p)F(|x| < R)\| \leq C_N(R + t)^{-N},$$

with C_N independent of R, t . States supported in momentum space in $\{|y| \leq v\}$, $v > 0$ are accounted for through scaling by $v > 0$: We apply the unitary dilation U satisfying $UpU^{-1} = p/v, UxU^{-1} = vx$ to the operator in the estimate above, replace t by v^2t and R by vR , the result being

$$\|F(|x| > \alpha(R + vt))e^{-itp^2/2} f(p/v)F(|x| < R)\| \leq C_N[v(R + vt)]^{-N}.$$

An estimate for the free Stark dynamics is readily obtained by means of the Avron-Herbst formula

$$e^{-itH_0} = T(t)e^{-itp^2/2}, \quad T(t) := e^{-ig^2t^3/6} e^{itg \cdot x} e^{-it^2g \cdot p/2}$$

and of $T(t)x = (x - gt^2/2)T(t)$, namely

$$\|F(|x - gt^2/2| > \alpha(R + vt))e^{-itH_0} f(p/v)F(|x| < R)\| \leq C_N[v(R + vt)]^{-N}. \quad (3)$$

Proof of Theorem 1 (existence). By Cook's theorem we have to show that

$$\int_0^\infty \|U(x, t)e^{-itH_0}\varphi\| dt < \infty$$

for φ in a dense set D , where $U(x, t) := V(x) - V(gt^2/2)$. Choosing

$$D := \{f(p/v)F(|x| < R)\psi \mid f \in C_0^\infty(|y| < 1), v, R > 0, \psi \in \mathcal{H}\},$$

this follows from

$$\begin{aligned} & \|U(x, t)e^{-itH_0} f(p/v)F(|x| < R)\psi\| \\ & \leq \|U(x, t)F(|x - gt^2/2| \leq \alpha(R + vt))\| \|\psi\| + C'_N[v(R + vt)]^{-N} \|\psi\| = O(t^{-1-2\epsilon}) \|\psi\|. \end{aligned} \quad (4)$$

Here we estimated the first term on the second line as follows: If $|x - gt^2/2| \leq \alpha(R + vt)$, then $U(x, t) = \nabla V(\tilde{x}) \cdot (x - gt^2/2)$ for some \tilde{x} with $|\tilde{x} - gt^2/2| \leq \alpha(R + vt)$. Then $|\tilde{x}| > |g|t^2/4$ for t large enough, and hence $\nabla V(\tilde{x}) = O(t^{-2(1+\epsilon)})$, proving (4). \square

Immediate consequences of the existence of the wave operator are that it is an isometry and that

$$\Omega = s\text{-}\lim_{s \rightarrow \infty} e^{isH} e^{-isH_0} e^{-i\Phi(s+t)} \quad (5)$$

for any $t \in \mathbb{R}$, since $\Phi(s+t) - \Phi(s) = \int_s^{s+t} V(g\tau^2/2) d\tau \rightarrow 0$ as $s \rightarrow \infty$. By comparing (5) with the definition (2) we get the intertwining relation $e^{itH}\Omega = \Omega e^{itH_0}$.

Another formulation of (3) is obtained using

$$e^{-itH_0}p = (p - gt)e^{-itH_0}, \quad e^{-itH_0}x = (x - pt + gt^2/2)e^{-itH_0},$$

which is

$$\|F(|x - gt^2/2| > \alpha(R+vt))f((p-gt)/v)F(|x - pt + gt^2/2| < R)\| \leq C_N[v(R+vt)]^{-N}. \tag{6}$$

The same remark also leads to

Corollary 2.

$$\lim_{t \rightarrow \infty} \|(\Omega - e^{-i\Phi(t)})f((p-gt)/v)F(|x - pt + gt^2/2| < R)\| = 0. \tag{7}$$

Proof. We apply Cook's estimate to (5) yielding

$$\|(\Omega - e^{-i\Phi(t)})e^{-itH_0}\varphi\| \leq \int_0^\infty \|U(x, s+t)e^{-i(s+t)H_0}\varphi\| ds = \int_t^\infty \|U(x, s)e^{-isH_0}\varphi\| ds.$$

We then set $\varphi = f(p/v)F(|x| < R)e^{itH_0}\psi$ and use (4). □

Let us now address the completeness question. We recall [2] that any $V \in L^\infty(\mathbb{R}^\nu)$ with $\lim_{x \rightarrow \infty} V(x) = 0$ is relatively compact with respect to H_0 and to H . This follows by density if it holds for V with compact support. In this case all terms in

$$\begin{aligned} V(H_0 + i)^{-1} - V(p^2/2 + i)^{-1} &= V(p^2/2 + i)^{-1}g \cdot x(H_0 + i)^{-1} \\ &= Vg \cdot x(p^2/2 + i)^{-1}(H_0 + i)^{-1} \\ &\quad + iV(p^2/2 + i)^{-1}g \cdot p(p^2/2 + i)^{-1}(H_0 + i)^{-1} \end{aligned}$$

are compact. We will also use that $\mathcal{H}_{cont} = \mathcal{H}$ for the spectral decomposition with respect to H [2]. Without using this result, one could prove that $\text{Ran } \Omega = \mathcal{H}_{cont}$ instead of unitarity of Ω by suitably modifying the proofs below.

Lemma 3. For $f \in C_\infty(\mathbb{R}^\nu)$

$$s\text{-}\lim_{t \rightarrow \infty} e^{itH} f\left(\frac{p-gt}{t}\right) e^{-itH} = f(0), \tag{8}$$

$$s\text{-}\lim_{t \rightarrow \infty} e^{itH} f\left(\frac{x-pt+gt^2/2}{t^2}\right) e^{-itH} = f(0). \tag{9}$$

Proof. We first remark that $D(p) \cap D(x)$ is invariant under e^{-itH} and that

$$\begin{aligned}
 e^{itH}(p - gt)e^{-itH}\psi &= p\psi - \int_0^t e^{isH}\nabla V(x)e^{-isH}\psi ds, \\
 e^{itH}(x - pt + gt^2/2)e^{-itH}\psi &= x\psi + \int_0^t se^{isH}\nabla V(x)e^{-isH}\psi ds
 \end{aligned}
 \tag{10}$$

for $\psi \in D(p) \cap D(x)$.

It suffices to prove the lemma for f depending on a single coordinate of its argument, since linear combinations of products of such functions are dense in $C_\infty(\mathbb{R}^\nu)$. By [7], Theorem VIII.20 (b) it is enough to show that (8, 9) hold for $f(y) = (y_i - z)^{-1}$, $z \notin \mathbb{R}$ and moreover strong and weak convergence are equivalent for resolvents. We thus set $p(t) := e^{itH}pe^{-itH}$, $x(t) := e^{itH}xe^{-itH}$ and have to show that for $\varphi \in \mathcal{H}$, $\psi \in D(p) \cap D(x)$

$$(\varphi, [(\frac{p_i(t) - g_i t}{t} - z)^{-1} - (-z)^{-1}]\psi) = z^{-1}((\frac{p_i(t) - g_i t}{t} - \bar{z})^{-1}\varphi, \frac{p_i(t) - g_i t}{t}\psi),$$

vanishes as $t \rightarrow \infty$. Indeed, by (10) this is bounded by a constant times

$$\frac{1}{t}\|p_i\psi\| + \frac{1}{t}\int_0^t \|\partial_i V(x)e^{-isH}\psi\| ds \xrightarrow{t \rightarrow \infty} 0.$$

The limit just stated holds by the RAGE theorem ([7], Theorem XI.115), because $\partial_i V$ is relatively compact with respect to H . The other observable is treated analogously. \square

Lemma 3 is still a rather weak result, since it roughly says that $p(t) - gt = o(t)$, $x(t) - p(t)t + gt^2/2 = o(t^2)$, while these quantities are constants of motion for the free Stark problem. The idea to improve this is the following: Let

$$S_t := \{(x, p) \mid |p - gt| < \delta t_0, |x - pt + gt^2/2| < \delta t_0^2\}$$

for some $\delta, t_0 > 0$. Classically S_{t_0} at time t_0 is mapped into S_t at time $t \geq t_0$ under the free Stark evolution. Moreover

$$\begin{aligned}
 |x - gt^2/2| &\leq |x - pt + gt^2/2| + t|p - gt| < \delta t_0(t + t_0) \leq 2\delta t^2, \\
 |x| &> (|g|/2 - 2\delta)t^2
 \end{aligned}$$

i.e. the particle is far from the scatterer if $\delta < |g|/4$. Therefore S_{t_0} should be mapped approximately in S_t also under the full dynamics.

Let $f \in C_0^\infty(\mathbb{R}^\nu)$ with $f(y) = 0$ for $|y| \geq \delta$ and set

$$\begin{aligned}
 f_1(t, t_0) &:= f\left(\frac{x - pt + gt^2/2}{t_0^2}\right), \quad f_2(t, t_0) := f\left(\frac{p - gt}{t_0}\right), \\
 \Theta(t, t_0) &:= f_1(t, t_0)^* f_2(t, t_0)^* f_2(t, t_0) f_1(t, t_0).
 \end{aligned}
 \tag{11}$$

Lemma 4. *If $\delta < |g|/4$, then*

$$\lim_{t_0 \rightarrow \infty} \sup_{t \geq t_0} \|e^{itH} \Theta(t, t_0) e^{-itH} - e^{it_0 H} \Theta(t_0, t_0) e^{-it_0 H}\| = 0. \tag{12}$$

Proof. The supremum in (12) is bounded by

$$\int_{t_0}^{\infty} \|D\Theta(t, t_0)\| dt, \tag{13}$$

where $D \cdot = i[H, \cdot] + \partial \cdot / \partial t$, i.e.

$$D\Theta = (Df_1)^* f_2^* f_2 f_1 + f_1^* (Df_2)^* f_2 f_1 + f_1^* f_2^* (Df_2) f_1 + f_1^* f_2^* f_2 (Df_1).$$

We start by computing

$$Df_1 = \int \hat{f}(s) i[V, e^{i(x-pt+gt^2/2)t_0^{-2} \cdot s}] ds = i \int \hat{f}(s) e^{i(x-pt+gt^2/2)t_0^{-2} \cdot s} (V(x+t_0^{-2}ts) - V(x)) ds$$

and split the integral into $|s| > t$ and $|s| \leq t$. The contribution to (13) of the first part is bounded by $O(t_0^{-N})$ for all $N > 0$, due to the decay of \hat{f} . For the other part, (6) implies that for $1 < \alpha < |g|(4\delta)^{-1}$

$$f_2^* f_2 f_1 = F(|x - gt^2/2| < \alpha\delta t_0(t + t_0)) f_2^* f_2 f_1 + O([t_0^2(t_0 + t)]^{-N}),$$

where the remainder contributes to (13) as little as $O(t_0^{-N})$. One is then left with estimating

$$\int_{|s| \leq t} |\hat{f}(s)| \| (V(x+t_0^{-2}ts) - V(x)) F(|x - gt^2/2| < \alpha\delta t_0(t + t_0)) \| ds \leq \text{const} \|s\hat{f}\|_1 t_0^{-2} t^{-(1+2\epsilon)},$$

contributing $O(t_0^{-2(1+\epsilon)})$ to (13). Here we used that if $|x - gt^2/2| < \alpha\delta t_0(t + t_0) \leq 2\alpha\delta t^2$ then $|V(x + t_0^{-2}ts) - V(x)| \leq t_0^{-2}t|s| |\nabla V(\tilde{x})|$ for some \tilde{x} with

$$|\tilde{x}| \geq |g|t^2/2 - |x - gt^2/2| - |x - \tilde{x}| \geq t^2(|g|/2 - 2\alpha\delta - t_0^{-2}),$$

where the bracket is positive for large t_0 . Terms arising from

$$Df_2 = i \int \hat{f}(s) e^{i(p-gt)t_0^{-1} \cdot s} (V(x - t_0^{-1}s) - V(x)) ds$$

are dealt with similarly. The integral restricted to $|s| \leq t$ is estimated up to a constant by $\|s\hat{f}\|_1 t_0^{-1} t^{-2(1+\epsilon)}$, its contribution to (13) thus by $O(t_0^{-2(1+\epsilon)})$. \square

Lemma 5. *Let f be as in the previous lemma, and real-valued with $f \leq 1$, $f(0) = 1$ in addition. Then*

$$\lim_{t_0 \rightarrow \infty} \sup_{t \geq t_0} \|(1 - f_2(t, t_0)f_1(t, t_0))e^{-itH}\psi\| = 0 \tag{14}$$

for any $\psi \in \mathcal{H}$.

Proof. Equations (8) and (9) imply $(e^{-it_0H}\psi, \Theta(t_0, t_0)e^{-it_0H}\psi) \rightarrow (\psi, \psi)$ as $t_0 \rightarrow \infty$. Then

$$\sup_{t \geq t_0} (\psi, \psi) - (e^{-itH}\psi, \Theta(t, t_0)e^{-itH}\psi) \xrightarrow{t_0 \rightarrow \infty} 0 \tag{15}$$

follows from (12). Suppressing arguments (t, t_0) we have $1 - f_2f_1 = (1 - f_1) + (1 - f_2)f_1$ and

$$\begin{aligned} \|(1 - f_1)e^{-itH}\psi\|^2 + \|(1 - f_2)f_1e^{-itH}\psi\|^2 \\ \leq (\|\psi\|^2 - \|f_1e^{-itH}\psi\|^2) + (\|f_1e^{-itH}\psi\|^2 - \|f_2f_1e^{-itH}\psi\|^2) \\ = (\psi, \psi) - (e^{-itH}\psi, \Theta(t, t_0)e^{-itH}\psi), \end{aligned}$$

since $f_i^2 \leq f_i$, $i = 1, 2$. Hence (14) is immediate from (15). □

Proof of Theorem 1 (completeness). Given $\psi \in \mathcal{H}$,

$$\begin{aligned} \|(\Omega - e^{-i\Phi(t)})e^{-itH}\psi\| \\ \leq \|(\Omega - e^{-i\Phi(t)})f_2(t, t_0)f_1(t, t_0)e^{-itH}\psi\| + 2\|(1 - f_2(t, t_0)f_1(t, t_0))e^{-itH}\psi\| \end{aligned}$$

can be made arbitrarily small due to (7, 14) by first choosing t_0 and then t large enough. Thus

$$\psi = e^{itH}\Omega e^{i\Phi(t)}e^{-itH}\psi + o(1) = \Omega e^{itH_0}e^{i\Phi(t)}e^{-itH}\psi + o(1)$$

as $t \rightarrow \infty$, implying $\psi \in \overline{\text{Ran } \Omega} = \text{Ran } \Omega$. □

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