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High frequency dispersive estimates in dimension two

SIMON MOULIN

Abstract

We prove dispersive estimates at high frequency in dimension two for both the wave and the Schrödinger groups for a very large class of real-valued potentials.

1 Introduction and statement of results

The purpose of this note is to prove dispersive estimates at high frequency for the wave group $e^{it\sqrt{G}}$ and the Schrödinger group e^{itG} , where G denotes the self-adjoint realization of the operator $-\Delta + V$ on $L^2(\mathbf{R}^2)$ and V is a real-valued potential which decays at infinity in a way that G has no real resonances nor eigenvalues in an interval $[a_0, +\infty)$, $a_0 > 0$. In fact, we are looking for as large as possible class of potentials for which we have dispersive estimates similar to those we do for the free operator G_0 . Hereafter G_0 denotes the self-adjoint realization of the operator $-\Delta$ on $L^2(\mathbf{R}^2)$. It turns out that in dimension two one can get such dispersive estimates at high frequency for potentials satisfying

$$\sup_{y \in \mathbf{R}^2} \int_{\mathbf{R}^2} \frac{|V(x)| dx}{|x-y|^{1/2}} \leq C < +\infty. \quad (1.1)$$

Clearly, (1.1) is fulfilled for potentials $V \in L^\infty(\mathbf{R}^2)$ satisfying

$$|V(x)| \leq C \langle x \rangle^{-\delta}, \quad \forall x \in \mathbf{R}^2, \quad (1.2)$$

with constants $C > 0$, $\delta > 3/2$. Given any $a > 0$, set $\chi_a(\sigma) = \chi_1(\sigma/a)$, where $\chi_1 \in C^\infty(\mathbf{R})$, $\chi_1(\sigma) = 0$ for $\sigma \leq 1$, $\chi_1(\sigma) = 1$ for $\sigma \geq 2$. Our first result is the following

Theorem 1.1 *Let V satisfy (1.1). Then, there exists a constant $a_0 > 0$ so that for every $a \geq a_0$, $0 < \epsilon \ll 1$, $2 \leq p < +\infty$, we have the estimates*

$$\left\| e^{it\sqrt{G}} G^{-3/4-\epsilon} \chi_a(G) \right\|_{L^1 \rightarrow L^\infty} \leq C_\epsilon |t|^{-1/2}, \quad t \neq 0, \quad (1.3)$$

$$\left\| e^{it\sqrt{G}} G^{-3\alpha/4} \chi_a(G) \right\|_{L^{p'} \rightarrow L^p} \leq C |t|^{-\alpha/2}, \quad t \neq 0, \quad (1.4)$$

where $1/p + 1/p' = 1$, $\alpha = 1 - 2/p$.

The estimate (1.3) is proved in [2] under the assumption (1.2). Moreover, if in addition one supposes that G has no strictly positive resonances, it is shown in [2] that (1.3) holds for any $a > 0$ still under (1.2). In dimension three an analogue of (1.3) is proved in [2], [4] for potentials satisfying (1.2) with $\delta > 2$, and extended in [3] to a large subset of potentials satisfying

$$\sup_{y \in \mathbf{R}^3} \int_{\mathbf{R}^3} \frac{|V(x)| dx}{|x-y|} \leq C < +\infty. \quad (1.5)$$

In dimensions $n \geq 4$ there are very few results. In [1], an analogue of (1.3) is proved for potentials belonging to the Schwartz class, while in [11] dispersive estimates with a loss of $(n-3)/2$ derivatives are obtained for potentials satisfying (1.2) with $\delta > (n+1)/2$. Recently, in [7] dispersive estimates at low frequency have been proved in dimensions $n \geq 4$ for a very large class of potentials, provided zero is neither an eigenvalue nor a resonance.

Our second result is the following

Theorem 1.2 *Let V satisfy (1.1). Then, there exists a constant $a_0 > 0$ so that for every $a \geq a_0$, we have the estimate*

$$\|e^{itG} \chi_a(G)\|_{L^1 \rightarrow L^\infty} \leq C|t|^{-1}, \quad t \neq 0. \quad (1.6)$$

Note that the estimate (1.6) (for any $a > 0$) is proved in [9] for potentials satisfying (1.2) with $\delta > 2$. In dimension three an analogue of (1.6) (for any $a > 0$) is proved in [10] for potentials satisfying (1.5) with $C > 0$ small enough, and in [5] for potentials $V \in L^{3/2-\epsilon} \cap L^{3/2+\epsilon}$, $0 < \epsilon \ll 1$, not necessarily small. In dimensions $n \geq 4$, an analogue of (1.6) (for any $a > 0$) is proved in [6] for potentials satisfying (1.2) with $\delta > n$ as well as the condition $\widehat{V} \in L^1$. This result has been recently extended in [8] to potentials satisfying (1.2) with $\delta > n-1$ and $\widehat{V} \in L^1$. Note also the work [12], where an analogue of (1.6) (for any $a > 0$) with a loss of $(n-3)/2$ derivatives is obtained for potentials satisfying (1.2) with $\delta > (n+2)/2$. In [8] dispersive estimates at low frequency have been also proved in dimensions $n \geq 4$ for a very large class of potentials, provided zero is neither an eigenvalue nor a resonance.

To prove (1.3) we use the same idea we have already used in [7] to prove low frequency dispersive estimates in dimensions $n \geq 4$. The key point is the following estimate which holds in all dimensions $n \geq 2$:

$$h \int_{-\infty}^{\infty} \left\| V e^{it\sqrt{G_0}} \psi(h^2 G_0) f \right\|_{L^1} dt \leq \gamma_n C_n(V) h^{-(n-3)/2} \|f\|_{L^1}, \quad h > 0, \quad (1.7)$$

where $\psi \in C_0^\infty((0, +\infty))$, $\gamma_n > 0$ is a constant independent of V , h and f , and

$$C_n(V) := \sup_{y \in \mathbf{R}^n} \int_{\mathbf{R}^n} \frac{|V(x)| dx}{|x-y|^{(n-1)/2}} < +\infty. \quad (1.8)$$

Our approach is based on the observation that if

$$C_n(V) h^{-(n-3)/2} \ll 1, \quad (1.9)$$

then (1.7) implies (under reasonable assumptions on the potential) a similar estimate for the perturbed wave group, namely

$$h \int_{-\infty}^{\infty} \left\| V e^{it\sqrt{G}} \psi(h^2 G) f \right\|_{L^1} dt \leq \tilde{C}_n(V) h^{-(n-3)/2} \|f\|_{L^1}. \quad (1.10)$$

When $n = 3$, (1.9) is fulfilled for small potentials and all h , when $n \geq 4$, (1.9) is fulfilled for large h (i.e. at low frequency) without extra restrictions on the potential, while for $n = 2$, (1.9) is fulfilled for small h (i.e. at high frequency) again without restrictions on the potential others than (1.1). Note that (1.10) may hold without (1.9). Indeed, when $n = 3$, (1.10) is proved in [5] for potentials $V \in L^{3/2-\epsilon} \cap L^{3/2+\epsilon}$ and all $h > 0$, and then used to prove the three dimensional analogue of (1.6). In the present paper we adapt this approach to the case of dimension two, and show that (1.6) follows from (1.10) for potentials satisfying (1.1) only, provided the parameter a is taken large enough (see Section 3).

2 Proof of Theorem 1.1

Let $\psi \in C_0^\infty((0, +\infty))$ and set

$$\Phi(t; h) = e^{it\sqrt{G}}\psi(h^2G) - e^{it\sqrt{G_0}}\psi(h^2G_0).$$

We will first show that (1.3) and (1.4) follow from the following

Proposition 2.1 *Let V satisfy (1.1). Then, there exist positive constants C and h_0 so that for $0 < h \leq h_0$ we have*

$$\|\Phi(t; h)\|_{L^1 \rightarrow L^\infty} \leq Ch^{-1}|t|^{-1/2}, \quad t \neq 0. \quad (2.1)$$

Writing

$$\sigma^{-3/4-\epsilon}\chi_a(\sigma) = \int_0^{a^{-1}} \psi(\sigma\theta)\theta^{-1/4+\epsilon}d\theta,$$

where $\psi(\sigma) = \sigma^{1/4-\epsilon}\chi_1'(\sigma) \in C_0^\infty((0, +\infty))$, and using (2.1) we get

$$\begin{aligned} & \left\| e^{it\sqrt{G}}G^{-3/4-\epsilon}\chi_a(G) - e^{it\sqrt{G_0}}G_0^{-3/4-\epsilon}\chi_a(G_0) \right\|_{L^1 \rightarrow L^\infty} \\ & \leq \int_0^{a^{-1}} \left\| \Phi(t; \sqrt{\theta}) \right\|_{L^1 \rightarrow L^\infty} \theta^{-1/4+\epsilon}d\theta \leq C|t|^{-1/2} \int_0^{a^{-1}} \theta^{-3/4+\epsilon}d\theta \leq C|t|^{-1/2}, \end{aligned} \quad (2.2)$$

provided a is taken large enough. Clearly, (1.3) follows from (2.2) and the fact that it holds for G_0 . To prove (1.4), observe that an interpolation between (2.1) and the trivial bound

$$\|\Phi(t; h)\|_{L^2 \rightarrow L^2} \leq C$$

yields

$$\|\Phi(t; h)\|_{L^{p'} \rightarrow L^p} \leq Ch^{-\alpha}|t|^{-\alpha/2}, \quad t \neq 0, \quad (2.3)$$

for every $2 \leq p \leq +\infty$, p' and α being as in Theorem 1.1. Now we write

$$\sigma^{-3\alpha/4}\chi_a(\sigma) = \int_0^{a^{-1}} \psi(\sigma\theta)\theta^{-1+3\alpha/4}d\theta,$$

and use (2.3) to obtain (for $0 < \alpha \leq 1$)

$$\begin{aligned} & \left\| e^{it\sqrt{G}}G^{-3\alpha/4}\chi_a(G) - e^{it\sqrt{G_0}}G_0^{-3\alpha/4}\chi_a(G_0) \right\|_{L^{p'} \rightarrow L^p} \\ & \leq \int_0^{a^{-1}} \left\| \Phi(t; \sqrt{\theta}) \right\|_{L^{p'} \rightarrow L^p} \theta^{-1+3\alpha/4}d\theta \leq C|t|^{-\alpha/2} \int_0^{a^{-1}} \theta^{-1+\alpha/4}d\theta \leq C|t|^{-\alpha/2}, \end{aligned} \quad (2.4)$$

provided a is taken large enough. Now, (1.4) follows from (2.4) and the fact that it holds for G_0 .

Proof of Proposition 2.1. We will first prove the following

Lemma 2.2 *Let V satisfy (1.1). Then, there exist positive constants C and h_0 so that for $0 < h \leq h_0$ we have*

$$\|\psi(h^2G) - \psi(h^2G_0)\|_{L^1 \rightarrow L^1} \leq Ch^{1/2}. \quad (2.5)$$

Proof. We will make use of the formula

$$\psi(h^2G) = \frac{2}{\pi} \int_{\mathbf{C}} \frac{\partial \tilde{\varphi}}{\partial \bar{z}}(z) (h^2G - z^2)^{-1} z L(dz), \quad (2.6)$$

where $L(dz)$ denotes the Lebesgue measure on \mathbf{C} , $\tilde{\varphi} \in C_0^\infty(\mathbf{C})$ is an almost analytic continuation of $\varphi(\lambda) = \psi(\lambda^2)$ supported in a small complex neighbourhood of $\text{supp } \varphi$ and satisfying

$$\left| \frac{\partial \tilde{\varphi}}{\partial \bar{z}}(z) \right| \leq C_N |\text{Im } z|^N, \quad \forall N \geq 1.$$

For $\pm \text{Im } \lambda \geq 0$, $\text{Re } \lambda > 0$, set

$$R_0^\pm(\lambda) = (G_0 - \lambda^2)^{-1}, \quad R^\pm(\lambda) = (G - \lambda^2)^{-1}.$$

We have the identity

$$R^\pm(\lambda) (1 + VR_0^\pm(\lambda)) = R_0^\pm(\lambda). \quad (2.7)$$

It is well known that the kernels of the operators $R_0^\pm(\lambda)$ are given in terms of the zero order Hankel functions by the formula

$$[R_0^\pm(\lambda)](x, y) = \pm i 4^{-1} H_0^\pm(\lambda |x - y|).$$

Moreover, the functions H_0^\pm satisfy the bound

$$|H_0^\pm(\lambda)| \leq C |\lambda|^{-1/2} e^{-|\text{Im } \lambda|}, \quad |\lambda| \geq 1, \quad \pm \text{Im } \lambda \geq 0, \quad (2.8)$$

while near $\lambda = 0$ they are of the form

$$H_0^\pm(\lambda) = a_{0,1}^\pm(\lambda) + a_{0,2}^\pm(\lambda) \log \lambda, \quad (2.9)$$

where $a_{0,j}^\pm$ are analytic functions. In particular, we have

$$|H_0^\pm(\lambda)| \leq C |\lambda|^{-1/2}, \quad \text{Re } \lambda > 0, \quad \pm \text{Im } \lambda \geq 0. \quad (2.10)$$

Using these bounds we will prove the following

Lemma 2.3 *Let V satisfy (1.1). Then, there exist constants $C > 0$ and $0 < h_0 \leq 1$ so that for $z \in \mathbf{C}_\varphi^\pm := \{z \in \text{supp } \tilde{\varphi}, \pm \text{Im } z \geq 0\}$, we have the estimates*

$$\|VR_0^\pm(z/h)\|_{L^1 \rightarrow L^1} \leq Ch^{1/2}, \quad 0 < h \leq 1, \quad (2.11)$$

$$\|VR^\pm(z/h)\|_{L^1 \rightarrow L^1} \leq Ch^{1/2}, \quad 0 < h \leq h_0, \quad (2.12)$$

$$\|R_0^\pm(z/h)\|_{L^1 \rightarrow L^1} \leq Ch^2 |\text{Im } z|^{-2}, \quad 0 < h \leq 1, \quad \text{Im } z \neq 0, \quad (2.13)$$

$$\|R^\pm(z/h)\|_{L^1 \rightarrow L^1} \leq Ch^2 |\text{Im } z|^{-2}, \quad 0 < h \leq h_0, \quad \text{Im } z \neq 0. \quad (2.14)$$

Proof. By (1.1) and (2.10), the norm in the LHS of (2.11) is upper bounded by

$$\sup_{y \in \mathbf{R}^2} \int_{\mathbf{R}^2} |V(x)| |H_0^\pm(z|x - y|/h)| dx \leq Ch^{1/2} \int_{\mathbf{R}^2} \frac{|V(x)| dx}{|x - y|^{1/2}} \leq C' h^{1/2}.$$

Similarly, the norm in the LHS of (2.13) is upper bounded by

$$\sup_{y \in \mathbf{R}^2} \int_{\mathbf{R}^2} |H_0^\pm(z|x - y|/h)| dx = h^2 \sup_{y \in \mathbf{R}^2} \int_{\mathbf{R}^2} |H_0^\pm(z|x - y|)| dx$$

$$\leq Ch^2 |\operatorname{Im} z|^{-2} \int_{\mathbf{R}^2} \langle x-y \rangle^{-3/2} |x-y|^{-1} dx = C'h^2 |\operatorname{Im} z|^{-2} \int_0^\infty \langle \sigma \rangle^{-3/2} d\sigma.$$

To prove (2.12) and (2.14) we will make use of the identity (2.7). It follows from (2.11) that there exists a constant $0 < h_0 \leq 1$ so that for $0 < h \leq h_0$ the operator $1 + VR_0^\pm(z/h)$ is invertible on L^1 with an inverse satisfying

$$\left\| (1 + VR_0^\pm(z/h))^{-1} \right\|_{L^1 \rightarrow L^1} \leq C, \quad z \in \mathbf{C}_\varphi^\pm, \quad (2.15)$$

with a constant $C > 0$ independent of z and h . Clearly, (2.12) follows from (2.11) and (2.15), while (2.14) follows from (2.13) and (2.15). \square

To prove (2.5) we rewrite the identity (2.7) in the form

$$R^\pm(z/h) - R_0^\pm(z/h) = R_0^\pm(z/h) VR_0^\pm(z/h) (1 + VR_0^\pm(z/h))^{-1},$$

and hence, using Lemma 2.3 and (2.15), we get

$$\left\| h^{-2} R^\pm(z/h) - h^{-2} R_0^\pm(z/h) \right\|_{L^1 \rightarrow L^1} \leq Ch^{1/2} |\operatorname{Im} z|^{-2}, \quad 0 < h \leq h_0, z \in \mathbf{C}_\varphi^\pm, \operatorname{Im} z \neq 0. \quad (2.16)$$

It is easy now to see that (2.5) follows from (2.6) and (2.16). \square

We will now derive (2.1) from the following

Proposition 2.4 *Let V satisfy (1.1). Then, there exist positive constants C and h_0 so that we have, for $0 \leq s \leq 1/2$, $0 < \epsilon \ll 1$, $f, g \in L^1$,*

$$\left\| e^{it\sqrt{G_0}} \psi(h^2 G_0) f \right\|_{L^\infty} \leq Ch^{-3/2} |t|^{-1/2} \|f\|_{L^1}, \quad h > 0, t \neq 0, \quad (2.17)$$

$$\begin{aligned} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^\infty |t|^s |x-y|^{-s} \left| V e^{it\sqrt{G_0}} \psi(h^2 G_0) f(x) \right| |g(y)| dt dx dy \\ \leq Ch^{-1/2} \|f\|_{L^1} \|g\|_{L^1}, \quad h > 0, \end{aligned} \quad (2.18)$$

$$\begin{aligned} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^\infty |t|^s \langle |x-y|/h \rangle^{-s} \left| V e^{it\sqrt{G}} \psi(h^2 G) f(x) \right| |g(y)| dt dx dy \\ \leq Ch^{s-1/2-\epsilon s} \|f\|_{L^1} \|g\|_{L^1}, \quad 0 < h \leq h_0. \end{aligned} \quad (2.19)$$

As in [12], using Duhamel's formula

$$e^{it\sqrt{G}} = e^{it\sqrt{G_0}} + i \frac{\sin(t\sqrt{G_0})}{\sqrt{G_0}} \left(\sqrt{G} - \sqrt{G_0} \right) - \int_0^t \frac{\sin((t-\tau)\sqrt{G_0})}{\sqrt{G_0}} V e^{i\tau\sqrt{G}} d\tau$$

we get the identity

$$\Phi(t; h) = \sum_{j=1}^2 \Phi_j(t; h), \quad (2.20)$$

where

$$\begin{aligned} \Phi_1(t; h) &= (\psi_1(h^2 G) - \psi_1(h^2 G_0)) e^{it\sqrt{G}} \psi(h^2 G) \\ &\quad + \psi_1(h^2 G_0) e^{it\sqrt{G_0}} (\psi(h^2 G) - \psi(h^2 G_0)) \\ &\quad - i \psi_1(h^2 G_0) \sin(t\sqrt{G_0}) (\psi(h^2 G) - \psi(h^2 G_0)) \\ &\quad + i \tilde{\psi}_1(h^2 G_0) \sin(t\sqrt{G_0}) (\tilde{\psi}(h^2 G) - \tilde{\psi}(h^2 G_0)), \end{aligned}$$

$$\Phi_2(t; h) = -h \int_0^t \tilde{\psi}_1(h^2 G_0) \sin\left((t-\tau)\sqrt{G_0}\right) V e^{i\tau\sqrt{G}} \psi(h^2 G) d\tau,$$

where $\psi_1 \in C_0^\infty((0, +\infty))$, $\psi_1 = 1$ on $\text{supp } \psi$, $\tilde{\psi}(\sigma) = \sigma^{1/2}\psi(\sigma)$, $\tilde{\psi}_1(\sigma) = \sigma^{-1/2}\psi_1(\sigma)$. By Proposition 2.4 and (2.5), we have

$$\begin{aligned} \|\Phi_1(t; h)f\|_{L^\infty} &\leq Ch^{-1}|t|^{-1/2}\|f\|_{L^1} + Ch^{1/2}\|\Phi(t; h)f\|_{L^\infty}, \quad (2.21) \\ &\quad t^{1/2}|\langle \Phi_2(t; h)f, g \rangle| \\ &\leq h \int_0^{t/2} (t-\tau)^{1/2} \left\| \sin\left((t-\tau)\sqrt{G_0}\right) \tilde{\psi}_1(h^2 G_0)g \right\|_{L^\infty} \left\| V e^{i\tau\sqrt{G}} \psi(h^2 G)f \right\|_{L^1} d\tau \\ &\quad + h \int_{t/2}^t \left\| V \sin\left((t-\tau)\sqrt{G_0}\right) \tilde{\psi}_1(h^2 G_0)g \right\|_{L^1} \tau^{1/2} \left\| e^{i\tau\sqrt{G}} \psi(h^2 G)f \right\|_{L^\infty} d\tau \\ &\leq Ch^{-1/2}\|g\|_{L^1} \int_{-\infty}^{\infty} \left\| V e^{i\tau\sqrt{G}} \psi(h^2 G)f \right\|_{L^1} d\tau \\ &\quad + h \sup_{t/2 \leq \tau \leq t} \tau^{1/2} \left\| e^{i\tau\sqrt{G}} \psi(h^2 G)f \right\|_{L^\infty} \int_{-\infty}^{\infty} \left\| V \sin\left((t-\tau)\sqrt{G_0}\right) \tilde{\psi}_1(h^2 G_0)g \right\|_{L^1} d\tau \\ &\leq Ch^{-1}\|g\|_{L^1}\|f\|_{L^1} + Ch^{1/2}\|g\|_{L^1} \sup_{t/2 \leq \tau \leq t} \tau^{1/2} \left\| e^{i\tau\sqrt{G}} \psi(h^2 G)f \right\|_{L^\infty}, \end{aligned}$$

for $t > 0$, which clearly implies

$$t^{1/2} \|\Phi_2(t; h)f\|_{L^\infty} \leq Ch^{-1}\|f\|_{L^1} + Ch^{1/2} \sup_{t/2 \leq \tau \leq t} \tau^{1/2} \left\| e^{i\tau\sqrt{G}} \psi(h^2 G)f \right\|_{L^\infty}. \quad (2.22)$$

By (2.20)-(2.22), we conclude

$$\begin{aligned} t^{1/2} \|\Phi(t; h)f\|_{L^\infty} &\leq Ch^{-1}\|f\|_{L^1} + Ch^{1/2}t^{1/2} \|\Phi(t; h)f\|_{L^\infty} \\ &\quad + Ch^{1/2} \sup_{t/2 \leq \tau \leq t} \tau^{1/2} \|\Phi(\tau; h)f\|_{L^\infty}. \quad (2.23) \end{aligned}$$

Taking h small enough we can absorb the second and the third terms in the RHS of (2.23), thus obtaining (2.1). Clearly, the case of $t < 0$ can be treated in the same way. \square

Proof of Proposition 2.3. The kernel of the operator $e^{it\sqrt{G_0}}\psi(h^2 G_0)$ is of the form $K_h(|x-y|, t)$, where

$$K_h(\sigma, t) = (2\pi)^{-1} \int_0^\infty e^{it\lambda} J_0(\sigma\lambda) \psi(h^2 \lambda^2) \lambda d\lambda = h^{-2} K_1(\sigma h^{-1}, t h^{-1}), \quad (2.24)$$

where $J_0(z) = (H_0^+(z) + H_0^-(z))/2$ is the Bessel function of order zero. It is shown in [12] (Section 2) that K_h satisfies the estimates (for all $\sigma, h > 0, t \neq 0$)

$$|K_1(\sigma, t)| \leq C|t|^{-s} \langle \sigma \rangle^{s-1/2}, \quad \forall s \geq 0, \quad (2.25)$$

$$|K_h(\sigma, t)| \leq Ch^{-3/2} |t|^{-s} \sigma^{s-1/2}, \quad 0 \leq s \leq 1/2. \quad (2.26)$$

Clearly, (2.17) follows from (2.26) with $s = 1/2$. We also have

$$\int_{-\infty}^{\infty} \langle t \rangle^s |K_1(\sigma, t)| dt \leq C \langle \sigma \rangle^{s-1/2}, \quad 0 \leq s \leq 1/2. \quad (2.27)$$

This estimate is proved in [7] (see the proof of Lemma 3.1) in all dimensions with $\langle t \rangle^s$ replaced by $|t|^s$, and it is easy to see that this implies (2.27). By (2.24) and (2.27), we get

$$\int_{-\infty}^{\infty} \langle t/h \rangle^s |K_h(\sigma, t)| dt \leq Ch^{-1} \langle \sigma/h \rangle^{s-1/2}, \quad 0 \leq s \leq 1/2, \quad (2.28)$$

which in turn implies

$$\int_{-\infty}^{\infty} |t|^s |K_h(\sigma, t)| dt \leq Ch^{-1/2} \sigma^{s-1/2}, \quad 0 \leq s \leq 1/2. \quad (2.29)$$

It is easy to see that (2.18) follows from (2.29) together with (1.1).

To prove (2.19) we will use the formula

$$e^{it\sqrt{G}}\psi(h^2G) = (i\pi h)^{-1} \int_0^{\infty} e^{it\lambda} \varphi_h(\lambda) (R^+(\lambda) - R^-(\lambda)) d\lambda, \quad (2.30)$$

where $\varphi_h(\lambda) = \varphi_1(h\lambda)$, $\varphi_1(\lambda) = \lambda\psi(\lambda^2)$. Combining (2.30) together with (2.7), we get

$$Ve^{it\sqrt{G}}\psi(h^2G) = (i\pi h)^{-1} \sum_{\pm} \int_{-\infty}^{\infty} VP_h^{\pm}(t-\tau)U_h^{\pm}(\tau)d\tau, \quad (2.31)$$

where

$$P_h^{\pm}(t) = \int_0^{\infty} e^{it\lambda} \tilde{\varphi}_h(\lambda) R_0^{\pm}(\lambda) d\lambda,$$

$$U_h^{\pm}(t) = \int_0^{\infty} e^{it\lambda} \varphi_h(\lambda) (1 + VR_0^{\pm}(\lambda))^{-1} d\lambda,$$

where $\tilde{\varphi}_h(\lambda) = \tilde{\varphi}_1(h\lambda)$, $\tilde{\varphi}_1 \in C_0^{\infty}((0, +\infty))$ is such that $\tilde{\varphi}_1 = 1$ on $\text{supp } \varphi_1$. The kernel of the operator $P_h^{\pm}(t)$ is of the form $A_h^{\pm}(|x-y|, t)$, where

$$A_h^{\pm}(\sigma, t) = \pm i4^{-1} \int_0^{\infty} e^{it\lambda} \tilde{\varphi}_h(\lambda) H_0^{\pm}(\sigma\lambda) d\lambda = h^{-1} A_1^{\pm}(\sigma/h, t/h). \quad (2.32)$$

In the same way as in the proof of (2.27) one can see that the functions A_1^{\pm} satisfy the estimate

$$\int_{-\infty}^{\infty} |t|^s |A_1^{\pm}(\sigma, t)| dt \leq C\sigma^{-\epsilon} \langle \sigma \rangle^{s+\epsilon-1/2}, \quad 0 \leq s \leq 1/2, \quad 0 < \epsilon \ll 1. \quad (2.33)$$

By (2.32) and (2.33), we have

$$\int_{-\infty}^{\infty} |t|^s |A_h^{\pm}(\sigma, t)| dt \leq Ch^{1/2} \sigma^{s-1/2} (1 + \sigma^{-\epsilon_s}), \quad 0 \leq s \leq 1/2, \quad 0 < h \leq 1, \quad (2.34)$$

where $\epsilon_s = 0$ if $0 \leq s < 1/2$, $\epsilon_s = \epsilon$ if $s = 1/2$.

Clearly, it suffices to prove (2.19) with $s = 0$ and $s = 1/2$. For these values of s , using (1.1), (2.31) and (2.34), we obtain

$$\begin{aligned} & \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} |t|^s \langle |x-y|/h \rangle^{-s} \left| Ve^{it\sqrt{G}}\psi(h^2G)f(x) \right| |g(y)| dt dx dy \\ & \leq Ch^{-1} \sum_{\pm} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \langle |x-y|/h \rangle^{-s} (|t-\tau|^s + |\tau|^s) \\ & \quad \times |VP_h^{\pm}(t-\tau)U_h^{\pm}(\tau)f(x)| |g(y)| d\tau dt dx dy \end{aligned}$$

$$\begin{aligned}
&\leq Ch^{-1} \sum_{\pm} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |V(x)| \langle |x-y|/h \rangle^{-s} (|t-\tau|^s + |\tau|^s) \\
&\quad \times |A_h^{\pm}(|x-x'|, t-\tau)| |U_h^{\pm}(\tau)f(x')| |g(y)| d\tau dt dx' dx dy \\
&\leq Ch^{-1} \sum_{\pm} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} |V(x)| \langle |x-y|/h \rangle^{-s} |g(y)| \\
&\quad \times \left(\int_{-\infty}^{\infty} |\tau|^s |A_h^{\pm}(|x-x'|, \tau)| d\tau \right) \left(\int_{-\infty}^{\infty} |U_h^{\pm}(\tau)f(x')| d\tau \right) dx' dx dy \\
&\quad + Ch^{-1} \sum_{\pm} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} |V(x)| \langle |x-y|/h \rangle^{-s} |g(y)| \\
&\quad \times \left(\int_{-\infty}^{\infty} |A_h^{\pm}(|x-x'|, \tau)| d\tau \right) \left(\int_{-\infty}^{\infty} |\tau|^s |U_h^{\pm}(\tau)f(x')| d\tau \right) dx' dx dy \\
&\leq Ch^{-1/2} \sum_{\pm} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} |V(x)| \langle |x-y|/h \rangle^{-s} |x-x'|^{s-1/2} (1+|x-x'|^{-\epsilon_s}) |g(y)| \\
&\quad \times \left(\int_{-\infty}^{\infty} |U_h^{\pm}(\tau)f(x')| d\tau \right) dx' dx dy \\
&\quad + Ch^{-1/2} \sum_{\pm} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} |V(x)| \langle |x-y|/h \rangle^{-s} |x-x'|^{-1/2} |g(y)| \\
&\quad \times \left(\int_{-\infty}^{\infty} |\tau|^s |U_h^{\pm}(\tau)f(x')| d\tau \right) dx' dx dy := I_1 + I_2. \tag{2.35}
\end{aligned}$$

To estimate I_1 when $s = 1/2$, set $q = (2\epsilon_{1/2})^{-1}$, $1/p + 1/q = 1$, and observe that in view of (1.1) we have the bound

$$\begin{aligned}
&\int_{\mathbf{R}^2} |V(x)| \langle |x-y|/h \rangle^{-1/2} |x-x'|^{-\epsilon_{1/2}} dx \\
&\leq \left(\int_{\mathbf{R}^2} |V(x)| \langle |x-y|/h \rangle^{-p/2} dx \right)^{1/p} \left(\int_{\mathbf{R}^2} |V(x)| |x-x'|^{-1/2} dx \right)^{1/q} \\
&\leq C_1 \left(\int_{\mathbf{R}^2} |V(x)| \langle |x-y|/h \rangle^{-1/2} dx \right)^{1/p} \\
&\leq C_1 h^{1/(2p)} \left(\int_{\mathbf{R}^2} |V(x)| |x-y|^{-1/2} dx \right)^{1/p} \leq C_2 h^{1/2-\epsilon_{1/2}}.
\end{aligned}$$

Thus, we obtain

$$I_1 \leq C' h^{s-1/2-\epsilon_s} \sum_{\pm} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} |U_h^{\pm}(\tau)f(x')| |g(y)| d\tau dx' dy. \tag{2.36}$$

To estimate I_2 when $s = 1/2$, we use the inequality

$$\langle |x-y|/h \rangle^{-1/2} |x-x'|^{-1/2} \leq \langle |x'-y|/h \rangle^{-1/2} (|x-y|^{-1/2} + |x-x'|^{-1/2}).$$

We get

$$I_2 \leq C'' h^{-1/2} \sum_{\pm} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} |\tau|^s \langle |x'-y|/h \rangle^{-s} |U_h^{\pm}(\tau)f(x')| |g(y)| d\tau dx' dy. \tag{2.37}$$

On the other hand, by the identity

$$(1 + VR_0^\pm(\lambda))^{-1} = 1 - VR_0^\pm(\lambda) (1 + VR_0^\pm(\lambda))^{-1},$$

we obtain

$$U_h^\pm(t) = \widehat{\varphi}_h(t) - \int_{-\infty}^{\infty} VP_h^\pm(t - \tau)U_h^\pm(\tau)d\tau. \quad (2.38)$$

Since

$$\widehat{\varphi}_h(t) = h^{-1}\widehat{\varphi}_1(t/h),$$

we have

$$\int_{-\infty}^{\infty} |t|^s |\widehat{\varphi}_h(t)| dt \leq Ch^s. \quad (2.39)$$

Using (2.38) and (2.39), in the same way as in the proof of (2.35)-(2.37), we obtain with $s = 0$ or $s = 1/2$,

$$\begin{aligned} & \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} |t|^s \langle |x - y|/h \rangle^{-s} |U_h^\pm(t)f(x)| |g(y)| dt dx dy \leq Ch^s \|f\|_{L^1} \|g\|_{L^1} \\ & + Ch^{s+1/2-\epsilon_s} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} |U_h^\pm(\tau)f(x')| |g(y)| d\tau dx' dy \\ & + Ch^{1/2} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} |\tau|^s \langle |x' - y|/h \rangle^{-s} |U_h^\pm(\tau)f(x')| |g(y)| d\tau dx' dy. \end{aligned} \quad (2.40)$$

Taking h small enough we can absorb the second and the third terms in the RHS of (2.40) and get the estimate

$$\int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} |t|^s \langle |x - y|/h \rangle^{-s} |U_h^\pm(t)f(x)| |g(y)| dt dx dy \leq C'h^s \|f\|_{L^1} \|g\|_{L^1}. \quad (2.41)$$

Now (2.19) follows from (2.35)-(2.37) and (2.41). \square

3 Proof of Theorem 1.2

Set

$$\Psi(t; h) = e^{itG}\psi(h^2G) - e^{itG_0}\psi(h^2G_0).$$

As in the previous section, one can derive (1.6) from the following

Proposition 3.1 *Let V satisfy (1.1). Then, there exist positive constants C and h_0 so that for $0 < h \leq h_0$, $0 < \epsilon \ll 1$, we have*

$$\|\Psi(t; h)\|_{L^1 \rightarrow L^\infty} \leq C_\epsilon h^{1/2-\epsilon} |t|^{-1}, \quad t \neq 0. \quad (3.1)$$

Proof. We will derive (3.1) from (2.19). To this end, we will use the identity

$$e^{it\lambda^2} \varphi(h^2\lambda^2) = \int_{-\infty}^{\infty} e^{i\tau\lambda} \zeta_h(t, \tau) d\tau, \quad (3.2)$$

where $\varphi \in C_0^\infty((0, +\infty))$, $\varphi = 1$ on $\text{supp } \psi_1$, the functions ψ and ψ_1 being as in the previous section, and

$$\zeta_h(t, \tau) = (2\pi)^{-1} \int_0^\infty e^{it\lambda^2 - i\tau\lambda} \varphi(h^2\lambda^2) d\lambda = h^{-1} \zeta_1(th^{-2}, \tau h^{-1}). \quad (3.3)$$

We deduce from (3.2) the formula

$$e^{itG}\psi(h^2G) = \int_{-\infty}^{\infty} \zeta_h(t, \tau) e^{i\tau\sqrt{G}} \psi(h^2G) d\tau. \quad (3.4)$$

Given any integer $m \geq 0$, integrating by parts m times and using the well known bound

$$\left| \int_{-\infty}^{\infty} e^{it\lambda^2 - i\tau\lambda} \phi(\lambda) d\lambda \right| \leq C|t|^{-1/2}, \quad \forall t \neq 0, \tau \in \mathbf{R},$$

where $\phi \in C_0^\infty(\mathbf{R})$, one easily obtains the bound

$$|\zeta_1(t, \tau)| \leq C_m |t|^{-m-1/2} \langle \tau \rangle^m, \quad \forall t \neq 0, \tau \in \mathbf{R}. \quad (3.5)$$

By (3.3) and (3.5),

$$|\zeta_h(t, \tau)| \leq C_m h^{2m} |t|^{-m-1/2} \langle \tau/h \rangle^m, \quad \forall t \neq 0, \tau \in \mathbf{R}, h > 0, \quad (3.6)$$

for every integer $m \geq 0$, and hence for all real $m \geq 0$. By (2.5), (2.20) and (3.4), we get

$$\begin{aligned} |\langle \Psi(t; h)f, g \rangle| &\leq Ch^{1/2} \|\Psi(t; h)f\|_{L^\infty} \|g\|_{L^1} \\ &+ \int_{-\infty}^{\infty} |\zeta_h(t, \tau)| \left| \left\langle e^{i\tau\sqrt{G_0}} \psi(h^2G_0)f, (\psi_1(h^2G) - \psi_1(h^2G_0))g \right\rangle \right| d\tau \\ &+ \int_{-\infty}^{\infty} |\zeta_h(t, \tau)| \left| \left\langle e^{i\tau\sqrt{G_0}} \psi_1(h^2G_0) (\psi(h^2G) - \psi(h^2G_0))f, g \right\rangle \right| d\tau \\ &+ \int_{-\infty}^{\infty} |\zeta_h(t, \tau)| \left| \left\langle \sin(\tau\sqrt{G_0}) \psi_1(h^2G_0) (\psi(h^2G) - \psi(h^2G_0))f, g \right\rangle \right| d\tau \\ &+ \int_{-\infty}^{\infty} |\zeta_h(t, \tau)| \left| \left\langle \sin(\tau\sqrt{G_0}) \tilde{\psi}_1(h^2G_0) (\tilde{\psi}(h^2G) - \tilde{\psi}(h^2G_0))f, g \right\rangle \right| d\tau \\ &+ h \int_{-\infty}^{\infty} \int_0^\tau |\zeta_h(t, \tau)| \left| \left\langle V e^{i\tau'\sqrt{G}} \psi(h^2G)f, \sin((\tau - \tau')\sqrt{G_0}) \tilde{\psi}_1(h^2G_0)g \right\rangle \right| d\tau' d\tau. \quad (3.7) \end{aligned}$$

Using (3.6) with $m = 1/2$ and (2.28) with $s = 1/2$ together with (2.5), we obtain that the first integral in the RHS of (3.7) is upper bounded by

$$\begin{aligned} &Ch|t|^{-1} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} \langle \tau/h \rangle^{1/2} |K_h(|x-y|, \tau)| |f(x)| |(\psi_1(h^2G) - \psi_1(h^2G_0))g(y)| d\tau dx dy \\ &\leq C|t|^{-1} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} |f(x)| |(\psi_1(h^2G) - \psi_1(h^2G_0))g(y)| dx dy \leq Ch^{1/2} |t|^{-1} \|f\|_{L^1} \|g\|_{L^1}, \end{aligned}$$

and similarly for the next three integrals. The last term is upper bounded by

$$\begin{aligned} &Ch^2 |t|^{-1} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} \int_0^\tau \left(|\tau'/h|^{1/2} + \langle (\tau - \tau')/h \rangle^{1/2} \right) \left| \tilde{K}_h(|x-y|, (\tau - \tau')) \right| \\ &\quad \times \left| V e^{i\tau'\sqrt{G}} \psi(h^2G)f(x) \right| |g(y)| d\tau' d\tau dx dy \\ &\leq Ch^{3/2} |t|^{-1} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} |\tau|^{1/2} \left| V e^{i\tau\sqrt{G}} \psi(h^2G)f(x) \right| |g(y)| d\tau \int_{-\infty}^{\infty} \left| \tilde{K}_h(|x-y|, \tau) \right| d\tau dx dy \\ &+ Ch^2 |t|^{-1} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} \left| V e^{i\tau\sqrt{G}} \psi(h^2G)f(x) \right| |g(y)| d\tau \int_{-\infty}^{\infty} \langle \tau/h \rangle^{1/2} \left| \tilde{K}_h(|x-y|, \tau) \right| d\tau dx dy \end{aligned}$$

$$\begin{aligned}
&\leq Ch^{1/2}|t|^{-1} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} |\tau|^{1/2} \langle |x-y|/h \rangle^{-1/2} \left| V e^{i\tau\sqrt{G}} \psi(h^2G)f(x) \right| |g(y)| d\tau dx dy \\
&\quad + Ch|t|^{-1} \int_{\mathbf{R}^2} \int_{\mathbf{R}^2} \int_{-\infty}^{\infty} \left| V e^{i\tau\sqrt{G}} \psi(h^2G)f(x) \right| |g(y)| d\tau dx dy \\
&\qquad\qquad\qquad \leq C_\epsilon h^{1/2-\epsilon} |t|^{-1} \|f\|_{L^1} \|g\|_{L^1},
\end{aligned}$$

where $\tilde{K}_h(|x-y|, t)$ denotes the kernel of the operator $\sin(t\sqrt{G_0}) \tilde{\psi}_1(h^2G_0)$, and we have used (2.19) together with the fact that the function $\tilde{K}_h(\sigma, t)$ satisfies (2.28). Thus, we obtain

$$|\langle \Psi(t; h)f, g \rangle| \leq Ch^{1/2} \|\Psi(t; h)f\|_{L^\infty} \|g\|_{L^1} + C_\epsilon h^{1/2-\epsilon} |t|^{-1} \|f\|_{L^1} \|g\|_{L^1},$$

which clearly implies (3.1), provided h is taken small enough. \square

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