Simultaneous identification of the diffusion coefficient and the potential for the Schrödinger operator with only one observation

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Abstract
This paper is devoted to proving a stability result for two independent coefficients for a Schrödinger operator in an unbounded strip. The result is obtained with only one observation on an unbounded subset of the boundary and the data of the solution at a fixed time on the whole domain.

1. Introduction

Let \( \Omega = \mathbb{R} \times (d, 2d) \) be an unbounded strip of \( \mathbb{R}^2 \) with a fixed width \( d > 0 \). Let \( v \) be the outward unit normal to \( \Omega \) on \( \Gamma = \partial \Omega \). We denote \( x = (x_1, x_2) \) and \( \Gamma = \Gamma^+ \cup \Gamma^- \), where \( \Gamma^+ = \{x \in \Gamma; \ x_2 = 2d \} \) and \( \Gamma^- = \{x \in \Gamma; \ x_2 = d \} \). We consider the following Schrödinger equation:

\[
\begin{align*}
Hq \:=
& \imath \partial_t q + a \Delta q + bq = 0 \quad \text{in} \quad \Omega \times (0, T), \\
q(x, t) &= F(x, t) \quad \text{on} \quad \partial \Omega \times (0, T), \\
q(x, 0) &= q_0(x) \quad \text{in} \quad \Omega,
\end{align*}
\]

where \( a \) and \( b \) are the real-valued functions such that \( a \in C^2(\Omega) \), \( b \in C^2(\Omega) \) and \( a(x) \geq a_{\min} > 0 \). Moreover, we assume that \( a \) is bounded and \( b \) and all its derivatives up to order 2 are bounded. If we assume that \( q_0 \) belongs to \( H^4(\Omega) \) and \( F \in H^2(0, T, H^2(\partial \Omega)) \cap H^1(0, T, H^2(\partial \Omega)) \cap H^1(0, T, L^2(\partial \Omega)) \), then (1.1) admits a solution in \( H^1(0, T, H^2(\Omega)) \cap H^1(0, T, L^2(\Omega)) \).

Our problem can be stated as follows:

Is it possible to determine the coefficients \( a \) and \( b \) from the measurement of \( \imath \partial_t (\partial^2 q) \) on \( \Gamma^+ \)?
Let \( q \) (resp. \( \tilde{q} \)) be a solution of (1.1) associated with \((a, b, F, q_0)\) (resp. \((\tilde{a}, \tilde{b}, F, q_0)\)). We assume that \( q_0 \) is a real-valued function.

Our main result is
\[
\|a - \tilde{a}\|^2_{L^2(\Omega)} + \|b - \tilde{b}\|^2_{L^2(\Omega)} \leq C \left\| \partial_\nu \left( \partial^2_t q - \partial^2_t \tilde{q} \right) \right\|^2_{L^2_0((-T,T) \times \Gamma^*)} + C \sum_{i=0}^2 \|\partial^i_t (q - \tilde{q})(\cdot, 0)\|^2_{H^1(\Omega)},
\]

where \( C \) is a positive constant which depends on \((\Omega, \Gamma, T)\) and where the above norms are weighted Sobolev norms.

This paper is an improvement of [10] in the sense that we simultaneously determine with only one observation, two independent coefficients, the diffusion coefficient and the potential. For that we use two important tools: Carleman estimate (2.4) and lemma 2.4.

Carleman inequalities constitute a very efficient tool to derive observability estimates. The method of Carleman estimates has been introduced in the field of inverse problems by Bukhgeim and Klibanov (see [5, 6, 13, 14]). Carleman estimate techniques are presented in [15] for standard coefficients inverse problems for both linear and nonlinear partial differential equations. These methods give a local Lipschitz stability around a single known solution.

A lot of work using the same strategy concern the wave equation (see [2, 3, 16]) and the heat equation (see [4, 12, 18]). For the determination of a time-independent potential in the Schrödinger evolution equation, we can refer to [11] for bounded domains and [10] for unbounded domains. We can also cite [17] where the authors use weight functions satisfying a relaxed pseudo-convexity condition which allows us to prove Carleman inequalities with less restrictive boundary observations.

To our knowledge, there are few results concerning the simultaneous identification of two coefficients with only one observation. In [11] a stability result is given for the particular case where each coefficient depends only on one variable \(a = a(x_2)\) and \(b = b(x_1)\) for the operator \(i \partial_t q + \nabla \cdot (a \nabla q) + bq\) in an unbounded strip of \(\mathbb{R}^2\). The authors give a stability result for the diffusion coefficient \(a\) and the potential \(b\) with only one observation in an unbounded part of the boundary.

A physical background could be the reconstruction of the diffusion coefficient and the potential in a strip in geophysics. There are also applications in quantum mechanics: inverse problems associated with curved quantum guides (see [7–9]).

This paper is organized as follows. Section 2 is devoted to some useful estimates. We first give an adapted global Carleman estimate for the operator \(H\). We then recall the crucial lemma given in [15]. In section 3 we state and prove our main result.

2. Some useful estimates

2.1. Global Carleman inequality

Let \( a \) be a real-valued function in \(C^3(\Omega)\) and \( b \) be a real-valued function in \(C^2(\overline{\Omega})\) such that

Assumption 2.1.

\( a \geq a_{\text{min}} > 0, a \) and all its derivatives up to order 3 are bounded;

\( b \) and its derivatives up to order 2 are bounded.

Let \( q(x, t) \) be a function equal to zero on \( \partial \Omega \times (-T, T) \) and a solution of the Schrödinger equation
\[
i \partial_t q + a \Delta q + bq = f.
\]
We prove here a global Carleman-type estimate for \( q \) with a single observation acting on a part \( \Gamma^* \) of the boundary \( \Gamma \) on the right-hand side of the estimate.

Note that this estimate is quite similar to the one obtained in [10], but the computations are different. Indeed, the weight function \( \beta \) does not satisfy the same pseudo-convexity assumptions (see assumption 2.2) and the decomposition of the operator \( H \) is different (see (2.2)).

Let \( \tilde{\beta} \) be a \( C^4(\overline{\Omega}) \) positive function such that there exist positive constants \( C_0, C_{pc} \) which satisfy

**Assumption 2.2.**

- \( |\nabla \tilde{\beta}| \geq C_0 > 0 \) in \( \Omega \), \( \partial_\nu \tilde{\beta} \leq 0 \) on \( \Gamma^* \).
- \( \tilde{\beta} \) and all its derivatives up to order 4 are bounded in \( \overline{\Omega} \).
- \( 2M |(D^2 \tilde{\beta}(\xi)) - \nabla a \cdot \nabla \tilde{\beta}|^2 + 2a^2 |\nabla \tilde{\beta} \cdot \xi|^2 \geq C_{pc} |\xi|^2 \), for all \( \xi \in \mathbb{C} \)

where

\[
D^2 \tilde{\beta} = \begin{pmatrix}
\partial_{x_1}(a^2 \partial_{x_2} \tilde{\beta}) & \partial_{x_3}(a^2 \partial_{x_2} \tilde{\beta}) \\
\partial_{x_2}(a^2 \partial_{x_3} \tilde{\beta}) & \partial_{x_3}(a^2 \partial_{x_3} \tilde{\beta})
\end{pmatrix}.
\]

Note that the last assertion of assumption 2.2 expresses the pseudo-convexity condition for the function \( \beta \). This assumption imposes restrictive conditions for the choice of the diffusion coefficient \( a \) in connection with the function \( \tilde{\beta} \) as in [10].

Note that there exist functions satisfying such assumptions. Indeed if we assume that \( \tilde{\beta}(x) := \tilde{\beta}(x_2) \), these conditions can be written in the following form:

\[
A = 2\partial_{x_2}(a^2 \partial_{x_2} \tilde{\beta}) - \partial_{x_2} a \partial_{x_2} \tilde{\beta} + 2a^2 (\partial_{x_2} \tilde{\beta})^2 \geq cst > 0
\]

and

\[
\frac{(\partial_{x_1}(a^2 \partial_{x_2} \tilde{\beta}))^2}{A} - \partial_{x_2} a \partial_{x_2} \tilde{\beta} \geq cst > 0.
\]

For example \( \tilde{\beta}(x) = e^{-x_2} \) with \( a(x) = \frac{1}{2}(x_2^2 + 5) \) satisfy the previous conditions (with \( x_2 \in (d, 2d) \)).

Then, we define \( \beta = \tilde{\beta} + K \) with \( K = m \| \tilde{\beta} \|_{\infty} \) and \( m > 1 \). For \( \lambda > 0 \) and \( t \in (-T, T) \), we define the following weight functions:

\[
\psi(x, t) = \frac{e^{\lambda \tilde{\beta}(x)}}{(T + t)(T - t)}, \quad \eta(x, t) = \frac{e^{2\lambda K - \lambda \tilde{\beta}(x)}}{(T + t)(T - t)}.
\]

We set \( \psi = e^{-s \eta}, M\psi = e^{s \eta}H(e^{s \eta} \psi) \) for \( s > 0 \). Let \( H \) be the operator defined by \( Hq := i\partial_\nu q + a\Delta q + bq \) in \( \Omega \times (-T, T) \).

Following [1], we introduce the operators

\[
M_1 \psi := i\partial_\nu \psi + a\Delta \psi + s^2 a|\nabla \eta|^2 \psi + (b - s \nabla \eta \cdot \nabla a) \psi,
\]

\[
M_2 \psi := is \partial_\nu \psi + 2as \nabla \eta \cdot \nabla \psi + s \nabla \cdot (a \nabla \eta) \psi.
\]

Then

\[
\int_{-T}^{T} \int_{\Omega} |M_1 \psi|^2 \, dx \, dt = \int_{-T}^{T} \int_{\Omega} |M_1 \psi|^2 \, dx \, dt + \int_{-T}^{T} \int_{\Omega} |M_2 \psi|^2 \, dx \, dt + 2\Re\left( \int_{-T}^{T} \int_{\Omega} M_1 \psi \overline{M_2 \psi} \, dx \, dt \right).
\]
where $\overline{z}$ is the conjugate of $z$, $\Re(z)$ its real part and $\Im(z)$ its imaginary part. Then the following result holds.

**Theorem 2.3.** Let $H$, $M_1$, $M_2$ be the operators defined respectively by (2.1), (2.2). We assume that assumptions 2.1 and 2.2 are satisfied. Then there exist $\lambda_0 > 0$, $s_0 > 0$ and a positive constant $C = C(\Omega, \Gamma, T)$ such that, for any $\lambda \geq \lambda_0$ and any $s \geq s_0$, the next inequality holds:

\[
\begin{align*}
&\quad s^4 \lambda^4 \int_{-T}^{T} \int_{\Omega} e^{-2s\eta}|q|^2 \, dx \, dt + s\lambda \int_{-T}^{T} \int_{\Omega} e^{-2s\eta} |\nabla q|^2 \, dx \, dt + \|M_1(e^{-s\eta}q)\|^2_{L^2(\Omega \times (-T,T))} \\
&+ \|M_2(e^{-s\eta}q)\|^2_{L^2(\Omega \times (-T,T))} \leq C s \lambda \int_{-T}^{T} \int_{\Gamma} e^{-2s\eta} |\partial_\nu q|^2 \, d\sigma \, dt \\
&+ \int_{-T}^{T} \int_{\Omega} e^{-2s\eta} |Hq|^2 \, dx \, dt,
\end{align*}
\]

for all $q$ satisfying $q \in L^2(-T, T; H_0^1(\Omega) \cap H^2(\Omega)) \cap H^1(-T, T; L^2(\Omega))$, $\partial_\nu q \in L^2(-T, T; L^2(\Gamma))$. Moreover, we have

\[
\begin{align*}
&\quad s^4 \lambda^4 \int_{-T}^{T} \int_{\Omega} e^{-2s\eta}|q|^2 \, dx \, dt + s\lambda \int_{-T}^{T} \int_{\Omega} e^{-2s\eta} |\nabla q|^2 \, dx \, dt + \|M_1(e^{-s\eta}q)\|^2_{L^2(\Omega \times (-T,T))} \\
&+ \|M_2(e^{-s\eta}q)\|^2_{L^2(\Omega \times (-T,T))} + s^{-1} \lambda^{-1} \int_{-T}^{T} \int_{\Omega} e^{-2s\eta} |i\partial_\nu q + a\Delta q|^2 \, dx \, dt \\
&\leq C \left[ s \lambda \int_{-T}^{T} \int_{\Gamma} e^{-2s\eta} |\partial_\nu q|^2 \, d\sigma \, dt + \int_{-T}^{T} \int_{\Omega} e^{-2s\eta} |Hq|^2 \, dx \, dt \right].
\end{align*}
\]

**Proof.** We have to estimate the scalar product

\[
\Re \left( \int_{-T}^{T} \int_{\Omega} M_1\psi M_2\overline{\psi} \, dx \, dt \right) = \sum_{i=1}^{4} \sum_{j=1}^{3} I_{ij}
\]

with

\[
\begin{align*}
I_{11} &= \Re \left( \int_{-T}^{T} \int_{\Gamma} (i\partial_\nu \psi)(-is\partial_\nu \overline{\psi}) \, dx \, dt \right), \\
I_{12} &= \Re \left( \int_{-T}^{T} \int_{\Gamma} (i\partial_\nu \psi) (2as \nabla \eta \cdot \nabla \overline{\psi}) \, dx \, dt \right), \\
I_{13} &= \Re \left( \int_{-T}^{T} \int_{\Gamma} (i\partial_\nu \psi) (s \nabla \cdot (a \nabla \eta) \overline{\psi}) \, dx \, dt \right), \\
I_{21} &= \Re \left( \int_{-T}^{T} \int_{\Gamma} (a\Delta \psi)(-is\partial_\nu \overline{\psi}) \, dx \, dt \right), \\
I_{22} &= \Re \left( \int_{-T}^{T} \int_{\Gamma} (a\Delta \psi)(2as \nabla \eta \cdot \nabla \overline{\psi}) \, dx \, dt \right), \\
I_{23} &= \Re \left( \int_{-T}^{T} \int_{\Gamma} (a\Delta \psi)(s \nabla \cdot (a \nabla \eta) \overline{\psi}) \, dx \, dt \right), \\
I_{31} &= \Re \left( \int_{-T}^{T} \int_{\Gamma} (s^2 a |\nabla \eta|^2 \psi)(-is\partial_\nu \overline{\psi}) \, dx \, dt \right), \\
I_{32} &= \Re \left( \int_{-T}^{T} \int_{\Gamma} (s^2 a |\nabla \eta|^2 \psi)(2as \nabla \eta \cdot \nabla \overline{\psi}) \, dx \, dt \right),
\end{align*}
\]
Following [1], using integrations by parts and Young estimates, we get (2.3). Moreover from (2.2) we have

\[ i \partial_t q + a \Delta q = M_1 q - s^2 a |\nabla \eta|^2 q + (b - s \nabla \eta \cdot \nabla a)q. \]

So

\[ i \partial_t q + a \Delta q = e^{i \eta} M_1 (e^{-i \eta} q) + is \partial_t \eta q - a e^{i \eta} \Delta (e^{-i \eta} q) - 2a e^{i \eta} \nabla (e^{-i \eta} \cdot \nabla q) - s^2 a |\nabla \eta|^2 q + (b - s \nabla \eta \cdot \nabla a)q. \]

And we deduce (2.4) from (2.3). □

### 2.2. The crucial lemma

We recall in this section the proof of a very important lemma proved by Klibanov and Timonov (see for example [14, 15]).

**Lemma 2.4.** There exists a positive constant \( \kappa \) such that

\[
\int_{-T}^{T} \int_{\Omega} \left| \int_{0}^{t} q(x, \xi) \, d\xi \right|^2 e^{-2s\eta} \, dx \, dt \leq \frac{\kappa}{s} \int_{-T}^{T} \int_{\Omega} |q(x, t)|^2 \, e^{-2s\eta} \, dx \, dt,
\]

for all \( s > 0 \).

**Proof.** By the Cauchy–Schwartz inequality, we have

\[
\int_{-T}^{T} \int_{\Omega} \left| \int_{0}^{t} q(x, \xi) \, d\xi \right|^2 e^{-2s\eta} \, dx \, dt \leq \int_{-T}^{T} \int_{\Omega} \left| t \right| \left( \int_{0}^{t} |q(x, \xi)|^2 \, d\xi \right) e^{-2s\eta} \, dx \, dt
\]
\[
\leq \int_{\Omega} \int_{0}^{t} t \left( \int_{0}^{t} |q(x, \xi)|^2 \, d\xi \right) e^{-2s\eta} \, dx \, dt
\]
\[
+ \int_{-T}^{T} \int_{\Omega} \left( \int_{0}^{t} |q(x, \xi)|^2 \, d\xi \right) e^{-2s\eta} \, dx \, dt.
\]

(2.5)

Note that

\[
\partial_t (e^{-2s\eta(x,t)}) = -2s(e^{2sK} - e^{2s\beta(x)})(T^2 - t^2) e^{-2s\eta(x,t)}. \]

So, if we denote \( \alpha(x) = e^{2sK} - e^{2s\beta(x)} \), we have

\[
t e^{-2s\eta(x,t)} = -\frac{(T^2 - t^2)^2}{4s\alpha(x)} \partial_t (e^{-2s\eta(x,t)}).
\]
For the first integral on the right-hand side of (2.5), by integration by parts we have
\[
\int_{\Omega} \int_{0}^{T} t \left( \int_{0}^{t} |q(x, \xi)|^2 \, d\xi \right) e^{-2s\eta} \, dx \, dt
= \int_{\Omega} \int_{0}^{T} \left( \int_{0}^{t} |q(x, \xi)|^2 \, d\xi \right) \frac{(T^2 - t^2)^2}{-4s\alpha(x)} \partial_t (e^{-2s\eta}) \, dx \, dt
= \int_{\Omega} \left[ \left( \int_{0}^{t} |q(x, \xi)|^2 \, d\xi \right) \frac{(T^2 - t^2)^2}{-4s\alpha(x)} e^{-2s\eta} \right]_{t=0}^{t=T} \, dx
+ \int_{\Omega} \int_{0}^{T} |q(x, t)|^2 \frac{(T^2 - t^2)^2}{4s\alpha(x)} e^{-2s\eta} \, dx \, dt
+ \int_{\Omega} \int_{0}^{T} \left( \int_{0}^{t} |q(x, \xi)|^2 \, d\xi \right) \frac{t(t^2 - T^2)}{s\alpha(x)} e^{-2s\eta} \, dx \, dt.
\]
Here we used \( \alpha(x) > 0 \) for all \( x \in \Omega \) and we obtain
\[
\int_{\Omega} \int_{0}^{T} t \left( \int_{0}^{t} |q(x, \xi)|^2 \, d\xi \right) e^{-2s\eta} \, dx \, dt
\leq \frac{1}{4s} \sup_{x \in \Omega} \left( \frac{1}{\alpha(x)} \right) \int_{\Omega} \int_{0}^{T} |q(x, t)|^2 e^{-2s\eta}(T^2 - t^2)^2 \, dx \, dt.
\]
Similarly for the second integral on the right-hand side of (2.5)
\[
\int_{\Omega} \int_{-T}^{0} (-t) \left( \int_{0}^{t} |q(x, \xi)|^2 \, d\xi \right) e^{-2s\eta} \, dx \, dt
\leq \frac{1}{4s} \sup_{x \in \Omega} \left( \frac{1}{\alpha(x)} \right) \int_{\Omega} \int_{-T}^{0} |q(x, t)|^2 e^{-2s\eta}(T^2 - t^2)^2 \, dx \, dt.
\]
Thus, the proof of lemma 2.4 is completed. \(\square\)

3. Stability result

In this section, we establish a stability inequality for the diffusion coefficient \( a \) and the potential \( b \).

Let \( q \in C^2(\Omega \times (0, T)) \) be a solution of
\[
\begin{cases}
  i\partial_t q + a D^2 q + bq = 0 & \text{in } \Omega \times (0, T), \\
  q(x, t) = F(x, t) & \text{on } \partial \Omega \times (0, T), \\
  q(x, 0) = q_0(x) & \text{in } \Omega,
\end{cases}
\]
and \( \tilde{q} \in C^2(\Omega \times (0, T)) \) be a solution of
\[
\begin{cases}
  i\partial_t \tilde{q} + \tilde{a} D^2 \tilde{q} + \tilde{b} \tilde{q} = 0 & \text{in } \Omega \times (0, T), \\
  \tilde{q}(x, t) = F(x, t) & \text{on } \partial \Omega \times (0, T), \\
  \tilde{q}(x, 0) = q_0(x) & \text{in } \Omega,
\end{cases}
\]
where \( (a, b) \) and \( (\tilde{a}, \tilde{b}) \) both satisfy assumption 2.1.

Assumption 3.1.

- All the time derivatives up to order 3 and the space derivatives up to order 4 for \( \tilde{q} \) exist and are bounded.
There exists a positive constant $C > 0$ such that $|\tilde{q}| \geq C$, $|\partial_t (\frac{\tilde{q}}{q})| \geq C$, $|\Delta \tilde{q}| \geq C$.

$q_0$ is a real-valued function.

Since $q_0$ is a real-valued function, we can extend the function $q$ (resp. $\tilde{q}$) on $\Omega \times (-T, T)$ by the formula $q(x, t) = \tilde{q}(x, -t)$ for every $(x, t) \in \Omega \times (-T, 0)$. Note that this extension satisfies the previous Carleman estimate. Our main stability result is

**Theorem 3.2.** Let $q$ and $\tilde{q}$ be the solutions of (1.1) in $C^2(\Omega \times (0, T))$ such that $q - \tilde{q} \in H^2((-T, T); H^2(\Omega))$. We assume that assumptions 2.1, 2.2, 3.1 are satisfied. Then there exists a positive constant $C = C(\Omega, \Gamma, T)$ such that for $s$ and $\lambda$ large enough,

$$\int_{-T}^{T} \int_{\Omega} e^{-2s}(|\tilde{a} - a|^2 + |\tilde{b} - b|^2) \, dx \, dt \leq C s \lambda^2 \int_{-T}^{T} \int_{\Gamma} \varphi e^{-2s} |\partial_{\nu} (\tilde{q}^2 - q^2)\partial_{\nu} (\tilde{q}^2 - q^2)|^2 \, d\sigma \, dt$$

$$+ C \lambda \int_{-T}^{T} \int_{\Omega} e^{-2s} \left( \sum_{i=0}^{2} |\partial_t^i (q - \tilde{q})(\cdot, 0)|^2 + |\nabla (q - \tilde{q})(\cdot, 0)|^2 \right. \right. \left. \left. + |\partial_t \nabla (q - \tilde{q})(\cdot, 0)|^2 + |\partial_t \Delta (q - \tilde{q})(\cdot, 0)|^2 \right) \, dx \, dt.$$  

Therefore,

$$\|a - \tilde{a}\|_{L^2(\Omega)}^2 + \|b - \tilde{b}\|_{L^2(\Omega)}^2 \leq C \left\| \partial_{\nu} (\tilde{q}^2 q) - \partial_{\nu} (\tilde{q}^2 \tilde{q}) \right\|_{L^2((-T, T) \times \Gamma)}^2$$

$$+ C \sum_{i=0}^{2} \left\| \partial_t^i (q - \tilde{q})(\cdot, 0) \right\|_{H^1(\Omega)}^2,$$

where the previous norms are weighted Sobolev norms.

**Proof.** We denote $u = q - \tilde{q}$, $\alpha = \tilde{a} - a$ and $\gamma = \tilde{b} - b$, so we get

$$\begin{cases}
i \partial_t u + a \Delta u + bu = \alpha \Delta \tilde{q} + \gamma \tilde{q} & \text{in } \Omega \times (-T, T), \\
u(x, t) = 0 & \text{on } \partial \Omega \times (-T, T), \\
u(x, 0) = 0 & \text{in } \Omega.
\end{cases}$$

(3.1)

The proof will be done in two steps: in the first step we prove an estimation for $\alpha$ and in the second step for $\gamma$.

**First step:** we set $u_1 = \frac{\gamma}{q}$. Then from (3.1) $u_1$ is a solution of

$$\begin{cases}
i \partial_t u_1 + a \Delta u_1 + bu_1 + A_{11} u_1 + B_{11} \cdot \nabla u_1 = \alpha \frac{\Delta \tilde{q}}{q} + \gamma & \text{in } \Omega \times (-T, T), \\
u_1(x, t) = 0 & \text{on } \partial \Omega \times (-T, T)
\end{cases}$$

where $A_{11} = \frac{\partial^2 \tilde{q}}{q^2} + a \frac{\Delta \tilde{q}}{q}$ and $B_{11} = \frac{2\Sigma \nabla \tilde{q}}{q}$.

Then defining $u_2 = \partial_t u_1$ we get that $u_2$ satisfies

$$\begin{cases}
i \partial_t u_2 + a \Delta u_2 + bu_2 + \Sigma_{i=1}^{2} A_{12} u_i + \Sigma_{i=1}^{2} B_{12} \cdot \nabla u_i = \alpha \frac{\Delta \tilde{q}}{q} & \text{in } \Omega \times (-T, T), \\
u_2(x, t) = 0 & \text{on } \partial \Omega \times (-T, T)
\end{cases}$$

where $A_{12} = \partial_t A_{11}$, $A_{22} = A_{11}$, $B_{12} = \partial_t B_{11}$, $B_{12} = B_{11}$.

Now let $u_3 = \frac{u_2}{\alpha (\frac{\Delta \tilde{q}}{q})}$; then $u_3$ is a solution of

$$\begin{cases}
i \partial_t u_3 + a \Delta u_3 + bu_3 + \Sigma_{i=1}^{3} A_{13} u_i + \Sigma_{i=1}^{3} B_{13} \cdot \nabla u_i = \alpha & \text{in } \Omega \times (-T, T), \\
u_3(x, t) = 0 & \text{on } \partial \Omega \times (-T, T)
\end{cases}$$

(3.2)
where $A_{13}$ and $B_{13}$ are bounded functions.

If we denote $g = \partial_t (\frac{\Delta u}{g})$, then

$$
A_{13} = \frac{1}{g} A_{12}, \quad A_{23} = \frac{1}{g} A_{22}, \quad A_{33} = \frac{1}{g} (i\partial_t g + \Delta g),
$$

$$
B_{13} = \frac{1}{g} B_{12}, \quad B_{23} = \frac{1}{g} B_{22}, \quad B_{33} = \frac{2a}{g} \nabla g.
$$

At last we define $u_4 = \partial_t u_3$ and $u_4$ satisfies

$$
\begin{align*}
\left\{ & i\partial_t u_4 + a \Delta u_4 + bu_4 + \sum_{i=1}^4 A_{i4} u_i + \sum_{i=1}^4 B_{i4} \cdot \nabla u_i = 0 \quad \text{in} \quad \Omega \times (-T, T), \\
& u_4(x, t) = 0 \quad \text{on} \quad \partial \Omega \times (-T, T)
\end{align*}
$$

where $A_{14}$ and $B_{14}$ are still bounded functions. Note that $A_{14} = \partial_t A_{13}$, $A_{24} = \partial_t A_{23} + A_{13}$, $A_{34} = \partial_t A_{33} + A_{23} \partial_t g + B_{23} \cdot \nabla (\partial_t g)$, $A_{44} = A_{23} g + A_{33} + B_{23} \cdot \nabla g$, $B_{14} = \partial_t B_{13}$, $B_{24} = \partial_t B_{23}$, $B_{34} = \partial_t B_{33} + \partial_t g B_{23}$, $B_{44} = B_{33} + g B_{23}$.

Applying the Carleman inequality (2.4) for $u_4$ we obtain (for $s$ and $\lambda$ sufficiently large)

$$
\begin{align*}
& s^3 \lambda^3 \int_{-T}^T \int_\Omega e^{-2\eta |u_4|^2} \, dx \, dt + s \lambda \int_{-T}^T \int_\Omega e^{-2\eta |\nabla u_4|^2} \, dx \, dt \\
& + s^{-1} \lambda^{-1} \int_{-T}^T \int_\Omega e^{-2\eta |i\partial_t u_4 + a \Delta u_4|^2} \, dx \, dt \\
\leq & C \left[ s \lambda \int_{-T}^T \int_\Omega e^{-2\eta |\partial_t u_4|^2} \partial_x \beta \, dx \, dt \\
& + \sum_{i=1}^3 \int_{-T}^T \int_\Omega e^{-2\eta (|u_i|^2 + |\nabla u_i|^2)} \, dx \, dt \right].
\end{align*}
$$

(3.3)

Note that $\int_{-T}^T \int_\Omega e^{-2\eta |u_1|^2} \, dx \, dt = \int_{-T}^T \int_\Omega e^{-2\eta |\partial_t u_1|^2} \, dx \, dt$, so from lemma 2.4 we get

$$
\int_{-T}^T \int_\Omega e^{-2\eta |u_1|^2} \, dx \, dt \leq C \int_{-T}^T \int_\Omega e^{-2\eta |u_3|^2} \, dx \, dt
$$

$$
\leq \frac{C}{s^2} \int_{-T}^T \int_\Omega e^{-2\eta |u_4|^2} \, dx \, dt + \frac{C}{s} \int_{-T}^T \int_\Omega e^{-2\eta |u_3|^2} \, dx \, dt.
$$

By the same way, we have

$$
\int_{-T}^T \int_\Omega e^{-2\eta |\nabla u_1|^2} \, dx \, dt \leq \frac{C}{s^2} \int_{-T}^T \int_\Omega e^{-2\eta |\nabla u_4|^2} \, dx \, dt
$$

$$
+ \frac{C}{s} \int_{-T}^T \int_\Omega e^{-2\eta |\nabla u_3|^2} \, dx \, dt + C \int_{-T}^T \int_\Omega e^{-2\eta |\nabla u_3|^2} \, dx \, dt.
$$

So (3.3) becomes

$$
\begin{align*}
& s^3 \lambda^3 \int_{-T}^T \int_\Omega e^{-2\eta |u_4|^2} \, dx \, dt + s \lambda \int_{-T}^T \int_\Omega e^{-2\eta |\nabla u_4|^2} \, dx \, dt \\
& + s^{-1} \lambda^{-1} \int_{-T}^T \int_\Omega e^{-2\eta |i\partial_t u_4 + a \Delta u_4|^2} \, dx \, dt \\
\leq & C s \lambda \int_{-T}^T \int_\Omega e^{-2\eta |\partial_t u_4|^2} \partial_x \beta \, dx \, dt \\
& + C \int_{-T}^T \int_\Omega e^{-2\eta (|u_3|^2 + |\nabla u_3|^2)} \, dx \, dt.
\end{align*}
$$

(3.4)
Furthermore, from (3.2) we have (with $C$ a positive constant)

$$|a|^2 \leq C \left( |i\partial_t u_3 + a\Delta u_3|^2 + \sum_{i=1}^{3} (|u_i|^2 + |\nabla u_i|^2) \right).$$

Therefore, for $s$ sufficiently large, from lemma 2.4

$$\int_{-T}^{T} \int_{\Omega} e^{-2\eta q} |a|^2 \, dx \, dt \leq \frac{C}{s} \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} (|i\partial_t u_4 + a\Delta u_4|^2 + |u_4|^2 + |\nabla u_4|^2) \, dx \, dt$$

$$+ C \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} (|i\partial_t u_3 + a\Delta u_3)(0)|^2 \, dx \, dt + C \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} |\nabla u_1(\cdot, 0)|^2 \, dx \, dt$$

$$+ C \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} (|u_3(\cdot, 0)|^2 + |\nabla u_3(\cdot, 0)|^2) \, dx \, dt.$$

Using (3.4) we get

$$\frac{1}{\lambda} \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} |a|^2 \, dx \, dt \leq C s \lambda \int_{-T}^{T} \int_{\Gamma} e^{-2\eta q} |\partial_t u_4|^2 \partial_t \beta \, d\sigma \, dt$$

$$+ \frac{C}{\lambda} \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} (|i\partial_t u_4 + a\Delta u_4|^2) \, dx \, dt$$

$$+ C \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} |\nabla u_1(\cdot, 0)|^2 \, dx \, dt$$

$$+ C \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} (|u_3(\cdot, 0)|^2 + |\nabla u_3(\cdot, 0)|^2) \, dx \, dt.$$

and then

$$\frac{1}{\lambda} \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} |a|^2 \, dx \, dt \leq C s \lambda \int_{-T}^{T} \int_{\Gamma} e^{-2\eta q} |\partial_t u_4|^2 \partial_t \beta \, d\sigma \, dt$$

$$+ C \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} \left( \sum_{i=0}^{2} |\partial_i u(\cdot, 0)|^2 + |\nabla u(\cdot, 0)|^2 \right) \, dx \, dt.$$

(3.5)

Second step: by the same way we obtain an estimation of $\gamma$. We set

$$v_1 = \frac{u}{\Delta Q}, \quad v_2 = \partial_t v_1, \quad v_3 = \frac{v_2}{\partial_t(\Delta Q)}.$$

Following the same methodology as in the first step, we obtain

$$\frac{1}{\lambda} \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} |\gamma|^2 \, dx \, dt \leq C s \lambda \int_{-T}^{T} \int_{\Gamma} e^{-2\eta q} |\partial_t u_4|^2 \partial_t \beta \, d\sigma \, dt$$

$$+ C \int_{-T}^{T} \int_{\Omega} e^{-2\eta q} \left( \sum_{i=0}^{2} |\partial_i u(\cdot, 0)|^2 + |\nabla u(\cdot, 0)|^2 \right) \, dx \, dt.$$

(3.6)

From (3.5) and (3.6) we can conclude

\[ \square \]
Remark 3.3.

(i) Note that the function $\tilde{q}(x, t) = e^{-it} + x^2 + 5$ with $\tilde{a}(x) = \frac{\sqrt{i}x^2}{2}$, $\tilde{b}(x) = -1$ satisfies assumption 3.1.

(ii) This method works for the Schrödinger operator in the divergential form:

$$i\partial_t q + \nabla \cdot (a\nabla q) + bq.$$  

We still obtain a similar stability result but with more restrictive hypotheses on the regularity of the function $\tilde{q}$.

Acknowledgments

We dedicate this paper to the memory of our friend and colleague Pierre Duclos, Professor at the University of Toulon in France.

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