

2013

## Weyl-Titchmarsh Type Formula for Periodic Schrodinger Operator with Wigner-von Neumann Potential

Sergey Simonov

*Technological University Dublin, sergey.a.simonov@gmail.com*

Pavel Kurasov

*Stockholm University*

Follow this and additional works at: <https://arrow.tudublin.ie/scschmatart>



Part of the [Mathematics Commons](#)

---

### Recommended Citation

Simonov, S., Kurasov, P. : (2013) Weyl-Titchmarsh Type Formula for Periodic Schrodinger Operator with Wigner-von Neumann Potential, Proceedings of the Royal Society of Edinburgh: Section A Mathematics, 143, pp 401-425. doi:10.1017/S0308210510001666.

This Article is brought to you for free and open access by the School of Mathematics at ARROW@TU Dublin. It has been accepted for inclusion in Articles by an authorized administrator of ARROW@TU Dublin. For more information, please contact [yvonne.desmond@tudublin.ie](mailto:yvonne.desmond@tudublin.ie), [arrow.admin@tudublin.ie](mailto:arrow.admin@tudublin.ie), [brian.widdis@tudublin.ie](mailto:brian.widdis@tudublin.ie).



This work is licensed under a [Creative Commons Attribution-NonCommercial-Share Alike 3.0 License](#)

# Weyl-Titchmarsh type formula for periodic Schrödinger operator with Wigner-von Neumann potential

Pavel Kurasov and Sergey Simonov

ABSTRACT. Schrödinger operator on the half-line with periodic background potential perturbed by a certain potential of Wigner-von Neumann type is considered. The asymptotics of generalized eigenvectors for  $\lambda \in \mathbb{C}_+$  and on the absolutely continuous spectrum is established. Weyl-Titchmarsh type formula for this operator is proven.

## 1. Introduction

Consider the one dimensional Schrödinger operator with the real potential which can be represented as a sum of three terms: a certain periodic function, Wigner-von Neumann potential and a certain absolutely integrable function. More precisely, let  $q$  be a real periodic function with period  $a$  such that  $q \in L_1(0; a)$  and let  $q_1 \in L_1(\mathbb{R}_+)$ . Then the Schrödinger operator  $\mathcal{L}_\alpha$  is defined by the differential expression

$$(1) \quad \mathcal{L}_\alpha := -\frac{d^2}{dx^2} + q(x) + \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma} + q_1(x),$$

on the set of functions satisfying the boundary condition

$$(2) \quad \psi(0) \cos \alpha - \psi'(0) \sin \alpha = 0,$$

where  $c, \omega, \delta \in \mathbb{R}$ ,  $\alpha \in [0, \pi)$ ,  $\gamma \in (\frac{1}{2}; 1]$ . As it was shown by the first author and Naboko in [16], the absolutely continuous spectrum of this

---

1991 *Mathematics Subject Classification.* 47E05, 34B20, 34L40, 34L20, 34E10.

*Key words and phrases.* Asymptotics of generalized eigenvectors, Weyl-Titchmarsh theory, Schrödinger operator, Wigner-von Neumann potential.

operator has multiplicity one and coincides as a set with the spectrum of the corresponding periodic operator on  $\mathbb{R}$ ,

$$(3) \quad \mathcal{L}_{per} = -\frac{d^2}{dx^2} + q(x).$$

Note that the spectrum of  $\mathcal{L}_{per}$  has multiplicity two. Let  $\psi_+(x, \lambda)$  and  $\psi_-(x, \lambda)$  be Bloch solutions for  $\mathcal{L}_{per}$  and  $\varphi_\alpha(x, \lambda)$  be the solution of Cauchy problem

$$\begin{aligned} -\varphi_\alpha''(x, \lambda) + \left( q(x) + \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma} + q_1(x) \right) \varphi_\alpha(x, \lambda) &= \lambda \varphi_\alpha(x, \lambda), \\ \varphi_\alpha(0, \lambda) &= \sin \alpha, \\ \varphi_\alpha'(0, \lambda) &= \cos \alpha. \end{aligned}$$

The main result of the present paper is the following theorem that relates the spectral density  $\rho'_\alpha$  of the operator  $\mathcal{L}_\alpha$  and the asymptotics of the solution  $\varphi_\alpha$ . We call it the Weyl-Titchmarsh formula.

**Theorem 1.** *Let  $\frac{2a\omega}{\pi} \notin \mathbb{Z}$  and  $q_1 \in L_1(\mathbb{R}_+)$ , then for almost all  $\lambda \in \sigma(\mathcal{L}_{per})$  there exists  $A_\alpha(\lambda)$  such that*

$$(4) \quad \varphi_\alpha(x, \lambda) = A_\alpha(\lambda)\psi_-(x, \lambda) + \overline{A_\alpha(\lambda)}\psi_+(x, \lambda) + o(1) \text{ as } x \rightarrow \infty$$

and

$$\rho'_\alpha(\lambda) = \frac{1}{2\pi |W(\psi_+(\lambda), \psi_-(\lambda))| |A_\alpha(\lambda)|^2}.$$

Weyl-Titchmarsh formulas form an efficient tool to study the behavior of the spectral density. The absolutely continuous spectrum of the operator  $\mathcal{L}_\alpha$  contains infinitely many critical (resonance) points (see (5)) where the type of the asymptotics of generalized eigenvectors changes and is not given by a linear combination of  $\psi_+$  and  $\psi_-$  (as in (4)). Precisely at these points the embedded eigenvalues of  $\mathcal{L}_\alpha$  may occur. In the generic case no eigenvalue occurs, but it is natural to suspect that the spectral density of  $\mathcal{L}_\alpha$  vanishes at these points.

Vanishing of the spectral density divides the absolutely continuous spectrum into independent parts and has a clear physical meaning. This phenomenon is called pseudogap. In the forthcoming paper we intend to study zeros of the spectral density in more detail.

The study of Schrödinger operators with Wigner-von Neumann potentials began from the classical paper [19] where it was observed for the first time that the potential  $\frac{c \sin(2\omega x + \delta)}{x+1}$  may produce an eigenvalue inside the absolutely continuous spectrum. Later on such operators attracted attention of many authors [1],[17],[18],[6],[2],[3],[4],[14],[15],[12],[13]. The phenomenon of this nature, an embedded eigenvalue ("bound state

in the continuum”), was even observed experimentally in semiconductor heterostructures [7].

Weyl-Titchmarsh formula for the spectral density in the case of zero periodic background potential follows directly from the results of [17]. This formula was proved once again in [2] where the method of Harris-Lutz transformations [11] was used. In the present paper we also use a modification of this method. We would like to mention that another one approach was suggested in [5], but again in the case of zero periodic background potential.

## 2. Preliminaries

The spectrum of  $\mathcal{L}_{per}$  consists of infinitely many intervals [9, Theorem 2.3.1]

$$\sigma(\mathcal{L}_{per}) := \bigcup_{n=0}^{\infty} ([\lambda_{2n}; \mu_{2n}] \cup [\mu_{2n+1}; \lambda_{2n+1}]),$$

where

$$\lambda_0 < \mu_0 \leq \mu_1 < \lambda_1 \leq \lambda_2 < \mu_2 \leq \mu_3 < \lambda_3 \leq \lambda_4 < \dots,$$

where  $\lambda_j$  and  $\mu_j$  are the eigenvalues of the Schrödinger differential equation on the interval  $[0, a]$  with periodic and antiperiodic boundary conditions. Spectral properties of  $\mathcal{L}_{per}$  are related to the entire function  $D(\lambda)$  (discriminant) and the function  $k(\lambda)$  (quasi-momentum)

$$k(\lambda) := -i \ln \left( \frac{\operatorname{tr} D(\lambda) + \sqrt{\operatorname{tr}^2 D(\lambda) - 4}}{2} \right).$$

We can choose the branch of  $k(\lambda)$  so that (this follows from the properties of  $D(\lambda)$ , see [9, Theorem 2.3.1])

$$\begin{aligned} k(\lambda_0) &= 0, k(\mu_0) = k(\mu_1) = \pi, k(\lambda_1) = k(\lambda_2) = 2\pi, \dots, \\ k(\lambda) &\in \mathbb{R}, \text{ if } \lambda \in \sigma(\mathcal{L}_{per}), \\ k(\lambda) &\in \mathbb{C}_+, \text{ if } \lambda \in \mathbb{C}_+. \end{aligned}$$

The eigenfunction equation for  $\mathcal{L}_{per}$ ,

$$-\psi''(x) + q(x)\psi(x) = \lambda\psi(x),$$

has two solutions (Bloch solutions)  $\psi_+(x, \lambda)$  and  $\psi_-(x, \lambda)$  satisfying quasiperiodic conditions:

$$\begin{aligned} \psi_+(x + a, \lambda) &\equiv e^{ik(\lambda)}\psi_+(x, \lambda), \\ \psi_-(x + a, \lambda) &\equiv e^{-ik(\lambda)}\psi_-(x, \lambda). \end{aligned}$$

They are determined uniquely up to multiplication by coefficients depending on  $\lambda$ . It is possible to choose these coefficients so that Bloch solutions have the following properties:

(1)  $\psi_+(x, \lambda), \psi_-(x, \lambda)$  for every  $x \geq 0$  and their Wronskian  $W(\psi_+(\lambda), \psi_-(\lambda))$  are analytic functions of  $\lambda$  in  $\mathbb{C}_+$  and continuous up to  $\sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, n \geq 0\}$ .

(2) For  $\lambda \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, n \geq 0\}$ ,

$$\psi_+(x, \lambda) \equiv \overline{\psi_-(x, \lambda)}.$$

(3) The Wronskian does not have zeros and for  $\lambda \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, n \geq 0\}$

$$W(\psi_+(\lambda), \psi_-(\lambda)) \in i\mathbb{R}_+.$$

Bloch solutions can also be written in the form

$$\begin{aligned} \psi_+(x, \lambda) &= e^{ik(\lambda)\frac{x}{a}} p_+(x, \lambda), \\ \psi_-(x, \lambda) &= e^{-ik(\lambda)\frac{x}{a}} p_-(x, \lambda), \end{aligned}$$

where the functions  $p_+(x, \lambda)$  and  $p_-(x, \lambda)$  have period  $a$  in the variable  $x$  and the same properties as  $\psi_+(x, \lambda)$  and  $\psi_-(x, \lambda)$  with respect to the variable  $\lambda$ .

As we mentioned earlier, the operator  $\mathcal{L}_\alpha$  was studied in [16], where the asymptotics of the generalized eigenvectors was obtained. The authors showed that in every zone of  $\sigma(\mathcal{L}_{per})$  ( $[\lambda_n; \mu_n]$  if  $n$  is even and  $[\mu_n; \lambda_n]$  if  $n$  is odd) there exist two critical points  $\lambda_n^+$  and  $\lambda_n^-$  determined by the equalities

$$(5) \quad \begin{aligned} k(\lambda_n^+) &= \pi \left( n + 1 - \left\{ \frac{a\omega}{\pi} \right\} \right), \\ k(\lambda_n^-) &= \pi \left( n + \left\{ \frac{a\omega}{\pi} \right\} \right). \end{aligned}$$

They do not coincide with each other and with the ends of zones, if

$$(6) \quad \frac{2a\omega}{\pi} \notin \mathbb{Z}.$$

### 3. Reduction of the spectral equation to the discrete linear system of Levinson form

In this section we transform the eigenfunction equation for  $\mathcal{L}_\alpha$  to a linear  $2 \times 2$  system with the coefficient matrix being a sum of the diagonal and summable matrices.

Consider the eigenfunction equation for  $\mathcal{L}_\alpha$ :

$$(7) \quad -\psi''(x) + \left( q(x) + \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma} + q_1(x) \right) \psi(x) = \lambda \psi(x).$$

For every

$$\lambda \in \mathbb{C}_+ \cup (\sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, n \geq 0\})$$

let us make the following substitution

$$(8) \quad \begin{pmatrix} \psi(x) \\ \psi'(x) \end{pmatrix} = \begin{pmatrix} \psi_-(x, \lambda) & \psi_+(x, \lambda) \\ \psi'_-(x, \lambda) & \psi'_+(x, \lambda) \end{pmatrix} u(x),$$

or

$$u(x) := \frac{1}{W(\psi_+(\lambda), \psi_-(\lambda))} \begin{pmatrix} \psi'_+(x, \lambda) & -\psi_+(x, \lambda) \\ -\psi'_-(x, \lambda) & \psi_-(x, \lambda) \end{pmatrix} \begin{pmatrix} \psi(x) \\ \psi'(x) \end{pmatrix}.$$

Writing (7) as

$$\begin{pmatrix} \psi(x) \\ \psi'(x) \end{pmatrix}' = \begin{pmatrix} 0 & 1 \\ q(x) + \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma} + q_1(x) - \lambda & 0 \end{pmatrix} \begin{pmatrix} \psi(x) \\ \psi'(x) \end{pmatrix}$$

and substituting (8) into it, we get:

$$(9) \quad u'(x) = \frac{\frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma} + q_1(x)}{W(\psi_+(\lambda), \psi_-(\lambda))} \begin{pmatrix} -\psi_+(x, \lambda)\psi_-(x, \lambda) & -\psi_+^2(x, \lambda) \\ \psi_-^2(x, \lambda) & \psi_+(x, \lambda)\psi_-(x, \lambda) \end{pmatrix} u(x).$$

Let us introduce another one vector valued function  $v$

$$(10) \quad v(x) := \begin{pmatrix} e^{-ik(\lambda)\frac{x}{a}} & 0 \\ 0 & e^{ik(\lambda)\frac{x}{a}} \end{pmatrix} u(x),$$

or

$$u(x) = \begin{pmatrix} e^{ik(\lambda)\frac{x}{a}} & 0 \\ 0 & e^{-ik(\lambda)\frac{x}{a}} \end{pmatrix} v(x)$$

and the matrix

$$(11) \quad R^{(1)}(x, \lambda) := \frac{q_1(x)}{W(\psi_+(\lambda), \psi_-(\lambda))} \begin{pmatrix} -p_+(x, \lambda)p_-(x, \lambda) & -p_+^2(x, \lambda) \\ p_-^2(x, \lambda) & p_+(x, \lambda)p_-(x, \lambda) \end{pmatrix}.$$

Then the system (9) is equivalent to

$$(12) \quad v'(x) = \left[ \begin{pmatrix} -\frac{ik(\lambda)}{a} & 0 \\ 0 & \frac{ik(\lambda)}{a} \end{pmatrix} + \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))} \right. \\ \left. \times \begin{pmatrix} -p_+(x, \lambda)p_-(x, \lambda) & -p_+^2(x, \lambda) \\ p_-^2(x, \lambda) & p_+(x, \lambda)p_-(x, \lambda) \end{pmatrix} + R^{(1)}(x, \lambda) \right] v(x).$$

Let us search for a differentiable matrix-valued function  $Q(x)$  such that  $Q(x), Q'(x) = O\left(\frac{1}{x^\gamma}\right)$  as  $x \rightarrow \infty$  and such that the substitution

$$(13) \quad v(x) = e^{Q(x)} \tilde{v}(x)$$

leads to a system for the vector valued function  $\tilde{v}$  of the form

$$\tilde{v}'(x) = \left[ \begin{pmatrix} -\frac{ik}{a} & 0 \\ 0 & \frac{ik}{a} \end{pmatrix} + \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma W(\psi_+, \psi_-)} \right. \\ \left. \times \begin{pmatrix} -p_+(x)p_-(x) & 0 \\ 0 & p_+(x)p_-(x) \end{pmatrix} + R^{(2)}(x) \right] \tilde{v}(x),$$

where the remainder  $R^{(2)}(x)$  also belongs to  $L_1(0, \infty)$ . Using that

$$e^{\pm Q(x)} = I \pm Q(x) + O\left(\frac{1}{x^{2\gamma}}\right), \\ (e^{\pm Q(x)})' = \pm Q'(x) + O\left(\frac{1}{x^{2\gamma}}\right)$$

as  $x \rightarrow \infty$  we obtain

$$(14) \quad \tilde{v}'(x) = \left[ \begin{pmatrix} -\frac{ik}{a} & 0 \\ 0 & \frac{ik}{a} \end{pmatrix} + \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma W(\psi_+, \psi_-)} \right. \\ \left. \times \begin{pmatrix} -p_+(x)p_-(x) & -p_+^2(x) \\ p_-^2(x) & p_+(x)p_-(x) \end{pmatrix} - Q'(x) \right. \\ \left. - \left[ Q(x), \begin{pmatrix} -\frac{ik}{a} & 0 \\ 0 & \frac{ik}{a} \end{pmatrix} \right] + R^{(1)}(x) + O\left(\frac{1}{x^{2\gamma}}\right) \right] \tilde{v}(x),$$

where

$$\left[ Q(x), \begin{pmatrix} -\frac{ik}{a} & 0 \\ 0 & \frac{ik}{a} \end{pmatrix} \right]$$

is the commutator of the two matrices. Our aim is to cancel the anti-diagonal entries of

$$\begin{pmatrix} -p_+(x)p_-(x) & -p_+^2(x) \\ p_-^2(x) & p_+(x)p_-(x) \end{pmatrix}$$

in (14) by properly choosing  $Q$ . To this end  $Q$  has to satisfy the following equation:

$$(15) \quad Q'(x) + \left[ Q(x), \begin{pmatrix} -\frac{ik}{a} & 0 \\ 0 & \frac{ik}{a} \end{pmatrix} \right] = \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma W(\psi_+, \psi_-)} \begin{pmatrix} 0 & -p_+^2(x) \\ p_-^2(x) & 0 \end{pmatrix}.$$

The latter is equivalent (after multiplication by  $\begin{pmatrix} e^{-ik\frac{x}{a}} & 0 \\ 0 & e^{ik\frac{x}{a}} \end{pmatrix}$  from the right and by its inverse from the left) to

$$(16) \quad \left( \begin{pmatrix} e^{ik\frac{x}{a}} & 0 \\ 0 & e^{-ik\frac{x}{a}} \end{pmatrix} Q(x) \begin{pmatrix} e^{-ik\frac{x}{a}} & 0 \\ 0 & e^{ik\frac{x}{a}} \end{pmatrix} \right)' \\ = \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma W(\psi_+, \psi_-)} \begin{pmatrix} 0 & -p_+^2(x)e^{2ik\frac{x}{a}} \\ p_-^2(x)e^{-2ik\frac{x}{a}} & 0 \end{pmatrix}.$$

For every

$$\mu \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, \lambda_n^+, \lambda_n^-, n \geq 0\}$$

and for the values of  $\lambda$  from some neighbourhood of the point  $\mu$  (which we will specify later) let us take the following solution of (16):

$$\begin{aligned} & \left( \begin{pmatrix} e^{ik\frac{x}{a}} & 0 \\ 0 & e^{-ik\frac{x}{a}} \end{pmatrix} Q(x, \lambda, \mu) \begin{pmatrix} e^{-ik\frac{x}{a}} & 0 \\ 0 & e^{ik\frac{x}{a}} \end{pmatrix} \right) = \frac{c}{W(\psi_+(\lambda), \psi_-(\lambda))} \\ & \times \begin{pmatrix} 0 & \int_x^\infty \frac{\sin(2\omega t + \delta) p_+^2(t, \lambda) e^{2ik(\lambda)\frac{t}{a}} dt}{(t+1)^\gamma} \\ \int_0^x \frac{\sin(2\omega t + \delta) p_-^2(t, \lambda) e^{-2ik(\lambda)\frac{t}{a}} dt}{(t+1)^\gamma} - \int_0^\infty \frac{\sin(2\omega t + \delta) p_-^2(t, \lambda) e^{-2ik(\mu)\frac{t}{a}} dt}{(t+1)^\gamma} & 0 \end{pmatrix} \end{aligned}$$

(this is our choice of constants of integration that depend on  $\mu$ ). This leads to

$$(17) \quad Q(x, \lambda, \mu) := \frac{c}{W(\psi_+(\lambda), \psi_-(\lambda))} \times \begin{pmatrix} 0 & e^{-2ik(\lambda)\frac{x}{a}} \int_x^\infty \frac{\sin(2\omega t + \delta) p_+^2(t, \lambda) e^{2ik(\lambda)\frac{t}{a}} dt}{(t+1)^\gamma} \\ e^{2ik(\lambda)\frac{x}{a}} \left( \int_0^x \frac{\sin(2\omega t + \delta) p_-^2(t, \lambda) e^{-2ik(\lambda)\frac{t}{a}} dt}{(t+1)^\gamma} - \int_0^\infty \frac{\sin(2\omega t + \delta) p_-^2(t, \lambda) e^{-2ik(\mu)\frac{t}{a}} dt}{(t+1)^\gamma} \right) & 0 \end{pmatrix}.$$

In particular, for  $\lambda = \mu$ ,

$$(18) \quad Q(x, \mu, \mu) = \frac{c}{W(\psi_+(\mu), \psi_-(\mu))} \times \begin{pmatrix} 0 & e^{-2ik(\mu)\frac{x}{a}} \int_x^\infty \frac{\sin(2\omega t + \delta) \psi_+^2(t, \mu) dt}{(t+1)^\gamma} \\ -e^{2ik(\mu)\frac{x}{a}} \int_x^\infty \frac{\sin(2\omega t + \delta) \psi_-^2(t, \mu) dt}{(t+1)^\gamma} & 0 \end{pmatrix}.$$

Formula (18) does not make sense if  $\mu \in \mathbb{C}_+$  due to the divergence of the integral in the lower entry. But it has analytic continuation in its second argument from the point  $\mu$ .

Let us denote

$$\varepsilon(\mu) := \frac{1}{2} \min_{n \in \mathbb{Z}} \left\{ \left| \frac{2k(\mu)}{a} + 2\omega + \frac{2\pi n}{a} \right|, \left| \frac{2k(\mu)}{a} - 2\omega + \frac{2\pi n}{a} \right| \right\}.$$

Consider some  $\beta > 0$  and the set

$$U(\beta, \mu) := \{ \lambda \in \overline{\mathbb{C}_+} : 2\varepsilon(\lambda) \geq \varepsilon(\mu), 0 \leq \operatorname{Im} 2k(\lambda)/a \leq 1, |\operatorname{Re} k(\lambda) - k(\mu)| \leq \beta \operatorname{Im} k(\lambda) \}.$$



The set  $U(\beta, \mu)$  is compact and contains the point  $\mu$ . For every  $\beta_1 < \beta$  it contains some neighbourhood of the vertex of the sector

$$|\operatorname{Re} \lambda - \mu| \leq \frac{\beta_1}{k'(\mu)} \operatorname{Im} \lambda.$$

Note that  $k'(\mu)$  is positive for  $\mu \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, n \geq 0\}$ .

**Theorem 2.** *Let  $\beta > 0$  and*

$$\mu \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, \lambda_n^+, \lambda_n^-, n \geq 0\}.$$

*Then there exists  $c_1(\beta, \mu, \gamma)$  such that for every  $x \geq 0$  and  $\lambda \in U(\beta, \mu)$  holds:*

$$\|Q(x, \lambda, \mu)\|, \|Q'(x, \lambda, \mu)\| < \frac{c_1(\beta, \mu, \gamma)}{(x+1)^\gamma}.$$

PROOF. Note first that

$$k(\lambda) \in \mathbb{R} \text{ for } \lambda \in \sigma(\mathcal{L}_{per})$$

and

$$k(\lambda) \in \mathbb{C}_+ \text{ for } \lambda \in \mathbb{C}_+.$$

Let us denote the entries of  $Q(x, \lambda, \mu)$  as follows

$$Q(x, \lambda, \mu) = \begin{pmatrix} 0 & Q_{12}(x, \lambda) \\ Q_{21}(x, \lambda, \mu) & 0 \end{pmatrix}.$$

Let us estimate first the entry  $Q_{12}$ . Let  $f$  be a periodic function with period  $a$  such that  $f \in L_1(0; a)$ , its Fourier coefficients will be denoted by  $f_n$

$$f_n := \frac{1}{a} \int_0^a f(x) e^{-2\pi i n \frac{x}{a}} dx.$$

**Lemma 1.** *If*

$$\{f_n\}_{n=-\infty}^{+\infty} \in l^1(\mathbb{Z})$$

*and  $\xi \in \overline{\mathbb{C}_+}$  is such that*

$$\frac{a\xi}{2\pi} \notin \mathbb{Z},$$

*then*

$$(19) \quad \left| e^{-i\xi x} \int_x^\infty \frac{e^{i\xi t} f(t) dt}{(t+1)^\gamma} \right| \leq 2 \left( \sum_{n=-\infty}^{+\infty} \frac{|f_n|}{\left| \xi - \frac{2\pi n}{a} \right|} \right) \frac{1}{(x+1)^\gamma}$$

*(i.e. the expression on the left-hand side exists and is estimated by the right-hand side).*

PROOF. Consider  $x_1 > x$ . Since the Fourier series converges absolutely, we have

$$(20) \quad e^{-i\xi x} \int_x^{x_1} \frac{e^{i\xi t}}{(t+1)^\gamma} \left( \sum_{n=-\infty}^{+\infty} f_n e^{2\pi n \frac{t}{a}} \right) dt = \sum_{n=-\infty}^{+\infty} f_n e^{-i\xi x} \int_x^{x_1} \frac{e^{i(\xi + \frac{2\pi n}{a})t}}{(t+1)^\gamma} dt.$$

Integrating by parts and estimating the absolute value we get

$$\begin{aligned} & \left| e^{-i\xi x} \int_x^{x_1} \frac{e^{i(\xi + \frac{2\pi n}{a})t}}{(t+1)^\gamma} dt \right| \leq \frac{1}{\left| \xi + \frac{2\pi n}{a} \right|} \\ & \times \left( \frac{1}{(x+1)^\gamma} + \frac{1}{(x_1+1)^\gamma} + \gamma \int_x^{x_1} \frac{dt}{(t+1)^{\gamma+1}} \right) = \frac{2}{\left| \xi + \frac{2\pi n}{a} \right| (x+1)^\gamma}. \end{aligned}$$

Substituting into (20) yields:

$$\left| e^{-i\xi x} \int_x^{x_1} \frac{e^{i\xi t} f(t) dt}{(t+1)^\gamma} \right| \leq 2 \left( \sum_{n=-\infty}^{+\infty} \frac{|f_n|}{\left| \xi - \frac{2\pi n}{a} \right|} \right) \frac{1}{(x+1)^\gamma}.$$

By Cauchy's criterion the integral

$$\int_x^\infty \frac{e^{i\xi t} f(t) dt}{(t+1)^\gamma}$$

exists and the desired estimate (19) follows.  $\square$

Formula (17) implies

$$(21) \quad \begin{aligned} Q_{12}(x, \lambda) &= \frac{ce^{2i\omega x + i\delta}}{2iW(\psi_+(\lambda), \psi_-(\lambda))} e^{-i(\frac{2k(\lambda)}{a} + 2\omega)x} \int_x^\infty \frac{p_+^2(t, \lambda) e^{i(\frac{2k(\lambda)}{a} + 2\omega)t}}{(t+1)^\gamma} dt \\ &\quad - \frac{ce^{-2i\omega x - i\delta}}{2iW(\psi_+(\lambda), \psi_-(\lambda))} e^{-i(\frac{2k(\lambda)}{a} - 2\omega)x} \int_x^\infty \frac{p_+^2(t, \lambda) e^{i(\frac{2k(\lambda)}{a} - 2\omega)t}}{(t+1)^\gamma} dt. \end{aligned}$$

Denote the Fourier coefficients of the function  $p_+^2(\cdot, \lambda)$  by  $b_n(\lambda)$ ,

$$b_n(\lambda) := \frac{1}{a} \int_0^a p_+^2(x, \lambda) e^{-2\pi i n \frac{x}{a}} dx.$$

Then Lemma 1 applied to (21) gives

$$\begin{aligned}
(22) \quad |Q_{12}(x, \lambda)| &\leq \frac{|c|}{|W(\psi_+(\lambda), \psi_-(\lambda))|} \frac{1}{(x+1)^\gamma} \\
&\times \sum_{n=-\infty}^{+\infty} |b_n(\lambda)| \left( \frac{1}{\left| \frac{2k(\lambda)}{a} + 2\omega + \frac{2\pi n}{a} \right|} + \frac{1}{\left| \frac{2k(\lambda)}{a} - 2\omega + \frac{2\pi n}{a} \right|} \right) \\
&\leq \frac{2|c|}{\varepsilon(\mu)|W(\psi_+(\lambda), \psi_-(\lambda))|} \left( \sum_{n=-\infty}^{+\infty} |b_n(\lambda)| \right) \frac{1}{(x+1)^\gamma}.
\end{aligned}$$

Let us estimate now the entry  $Q_{21}$ . Formula (17) implies

$$\begin{aligned}
Q_{21}(x, \lambda, \mu) &= \frac{ce^{2ik(\lambda)\frac{x}{a}}}{W(\psi_+(\lambda), \psi_-(\lambda))} \left( \int_0^x \frac{\sin(2\omega t + \delta)p_-^2(t, \lambda)e^{-2ik(\lambda)\frac{t}{a}} dt}{(t+1)^\gamma} \right. \\
&\quad \left. - \int_0^\infty \frac{\sin(2\omega t + \delta)p_-^2(t, \lambda)e^{-2ik(\mu)\frac{t}{a}} dt}{(t+1)^\gamma} \right) \\
&= \frac{ce^{2ik(\lambda)\frac{x}{a}}}{W(\psi_+(\lambda), \psi_-(\lambda))} \int_0^x \frac{\sin(2\omega t + \delta)p_-^2(t, \lambda) \left( e^{-2ik(\lambda)\frac{t}{a}} - e^{-2ik(\mu)\frac{t}{a}} \right) dt}{(t+1)^\gamma} \\
&\quad - \frac{ce^{2ik(\lambda)\frac{x}{a}}}{W(\psi_+(\lambda), \psi_-(\lambda))} \int_x^\infty \frac{\sin(2\omega t + \delta)p_-^2(t, \lambda)e^{-2ik(\mu)\frac{t}{a}} dt}{(t+1)^\gamma}.
\end{aligned}$$

Denote

$$\begin{aligned}
Q_{21}^I(x, \lambda, \mu) &:= \frac{ce^{2ik(\lambda)\frac{x}{a}}}{W(\psi_+(\lambda), \psi_-(\lambda))} \\
&\quad \times \int_0^x \frac{\sin(2\omega t + \delta)p_-^2(t, \lambda) \left( e^{-2ik(\lambda)\frac{t}{a}} - e^{-2ik(\mu)\frac{t}{a}} \right) dt}{(t+1)^\gamma}
\end{aligned}$$

and

$$Q_{21}^{II}(x, \lambda, \mu) := -\frac{ce^{2ik(\lambda)\frac{x}{a}}}{W(\psi_+(\lambda), \psi_-(\lambda))} \int_x^\infty \frac{\sin(2\omega t + \delta)p_-^2(t, \lambda)e^{-2ik(\mu)\frac{t}{a}} dt}{(t+1)^\gamma},$$

so that

$$Q_{21}(x, \lambda, \mu) = Q_{21}^I(x, \lambda, \mu) + Q_{21}^{II}(x, \lambda, \mu).$$

The second term can be estimated in the same manner as  $Q_{12}(x, \lambda)$  using Lemma 1. Denote by

$$\hat{b}_n(\lambda) := \frac{1}{a} \int_0^a p_-^2(x, \lambda) e^{-2\pi i n \frac{x}{a}} dx$$

the Fourier coefficients of  $p_-^2(\cdot, \lambda)$ . Then

$$(23) \quad |Q_{21}^{II}(x, \lambda, \mu)| \leq \frac{|c|}{|W(\psi_+(\lambda), \psi_-(\lambda))|} \frac{1}{(x+1)^\gamma} \\ \times \sum_{n=-\infty}^{+\infty} |\hat{b}_n(\lambda)| \left( \frac{1}{\left| \frac{2k(\lambda)}{a} - 2\omega - \frac{2\pi n}{a} \right|} + \frac{1}{\left| \frac{2k(\lambda)}{a} + 2\omega - \frac{2\pi n}{a} \right|} \right) \\ \leq \frac{2|c|}{\varepsilon(\mu)|W(\psi_+(\lambda), \psi_-(\lambda))|} \left( \sum_{n=-\infty}^{+\infty} |\hat{b}_n(\lambda)| \right) \frac{1}{(x+1)^\gamma}$$

(using that  $k(\mu) \in \mathbb{R}$  and  $k(\lambda) \in \overline{\mathbb{C}_+}$ ).

To estimate  $Q_{21}^I$  we shall need the following lemma:

**Lemma 2.** *Let  $\varepsilon, \beta > 0$ , then there exists  $c_2(\varepsilon, \beta, \gamma)$  such that for every  $\xi_1$  and  $\xi_2$  such that*

$$0 \leq \text{Im } \xi_1 \leq 1, \quad |\xi_1| \geq \varepsilon, \\ \xi_2 \in \mathbb{R}, \quad |\xi_2| \geq \varepsilon, \\ |\text{Re } \xi_1 - \xi_2| \leq \beta \text{Im } \xi_1$$

and for every  $x \geq 0$  holds:

$$\left| e^{i\xi_1 x} \int_0^x \frac{(e^{-i\xi_1 t} - e^{-i\xi_2 t}) dt}{(t+1)^\gamma} \right| < \frac{c_2(\varepsilon, \beta, \gamma)}{(x+1)^\gamma}.$$

PROOF. Integrating by parts we get

$$e^{i\xi_1 x} \int_0^x \frac{(e^{-i\xi_1 t} - e^{-i\xi_2 t}) dt}{(t+1)^\gamma} = \frac{ie^{i\xi_1 x}(\xi_1 - \xi_2)}{i\xi_1 \xi_2} + \frac{e^{i(\xi_1 - \xi_2)x}}{i\xi_2(x+1)^\gamma} \\ + \frac{i}{\xi_1(x+1)^\gamma} + \frac{\gamma e^{i\xi_1 x}(\xi_1 - \xi_2)}{i\xi_1 \xi_2} \int_0^x \frac{e^{-i\xi_2 t} dt}{(t+1)^{\gamma+1}} \\ - \frac{\gamma e^{i\xi_1 x}}{i\xi_1} \int_0^x \frac{(e^{-i\xi_1 t} - e^{-i\xi_2 t}) dt}{(t+1)^{\gamma+1}}.$$

Consider the new constant

$$c_3(\gamma) := \max_{x \geq 0} x^\gamma e^{-x}.$$

For every  $x \geq 0$  and  $\xi_1$  considered,

$$(\operatorname{Im} \xi_1)^\gamma e^{-\operatorname{Im} \xi_1 x} \leq \frac{c_3(\gamma) e^{\operatorname{Im} \xi_1}}{(x+1)^\gamma} \leq \frac{ec_3(\gamma)}{(x+1)^\gamma}.$$

Using that

$$|\operatorname{Re} \xi_1 - \xi_2| \leq \beta \operatorname{Im} \xi_1,$$

which is equivalent to

$$|\xi_1 - \xi_2| \leq \sqrt{\beta^2 + 1} \operatorname{Im} \xi_1,$$

and the integral can be estimated as

$$\begin{aligned} \left| e^{i\xi_1 x} \int_0^x \frac{(e^{-i\xi_1 t} - e^{-i\xi_2 t}) dt}{(t+1)^\gamma} \right| &\leq \frac{2ec_3(\gamma)\sqrt{\beta^2+1}}{\varepsilon^2(x+1)^\gamma} + \frac{2}{\varepsilon(x+1)^\gamma} \\ &\quad + \frac{\gamma}{\varepsilon} \left| e^{i\xi_1 x} \int_0^x \frac{(e^{-i\xi_1 t} - e^{-i\xi_2 t}) dt}{(t+1)^{\gamma+1}} \right|. \end{aligned}$$

The last term can be split into three parts as follows:

$$\begin{aligned} \left| e^{i\xi_1 x} \int_0^x \frac{(e^{-i\xi_1 t} - e^{-i\xi_2 t}) dt}{(t+1)^{\gamma+1}} \right| \\ \leq e^{-\operatorname{Im} \xi_1 x} \left[ \int_0^{\frac{1}{\operatorname{Im} \xi_1}} + \int_{\frac{1}{\operatorname{Im} \xi_1}}^{\frac{x}{2}} + \int_{\frac{x}{2}}^x \right] \frac{|e^{-i\xi_1 t} - e^{-i\xi_2 t}| dt}{(t+1)^{\gamma+1}}. \end{aligned}$$

Let us estimate these three integrals separately.

(1)

$$e^{-\operatorname{Im} \xi_1 x} \int_0^{\frac{1}{\operatorname{Im} \xi_1}} \frac{|e^{-i\xi_1 t} - e^{-i\xi_2 t}| dt}{(t+1)^{\gamma+1}} = e^{-\operatorname{Im} \xi_1 x} \int_0^{\frac{1}{\operatorname{Im} \xi_1}} \frac{|e^{-i(\xi_1 - \xi_2)t} - 1| dt}{(t+1)^{\gamma+1}}.$$

Introduce the constant

$$c_4(\beta) := \max_{|x| \leq \sqrt{\beta^2+1}} \frac{|e^x - 1|}{|x|}.$$

Since for the first interval

$$|-i(\xi_1 - \xi_2)t| \leq \frac{|\xi_1 - \xi_2|}{\operatorname{Im} \xi_1} \leq \sqrt{\beta^2 + 1},$$

we have:

$$\begin{aligned}
e^{-\operatorname{Im} \xi_1 x} \int_0^{\frac{1}{\operatorname{Im} \xi_1}} \frac{|e^{-i\xi_1 t} - e^{-i\xi_2 t}|}{(t+1)^{\gamma+1}} dt &\leq e^{-\operatorname{Im} \xi_1 x} \int_0^{\frac{1}{\operatorname{Im} \xi_1}} \frac{c_4(\beta) \sqrt{\beta^2 + 1} \operatorname{Im} \xi_1 t dt}{(t+1)^{\gamma+1}} \\
&\leq \frac{ec_3(\gamma)c_4(\beta)\sqrt{\beta^2 + 1}(\operatorname{Im} \xi_1)^{1-\gamma}}{(x+1)^\gamma} \int_0^{\frac{1}{\operatorname{Im} \xi_1}} \frac{dt}{(t+1)^\gamma} \\
&= \frac{ec_3(\gamma)c_4(\beta)\sqrt{\beta^2 + 1}((1 + \operatorname{Im} \xi_1)^{1-\gamma} - (\operatorname{Im} \xi_1)^{1-\gamma})}{(x+1)^\gamma(1-\gamma)} \\
&\leq \frac{2^{1-\gamma}ec_3(\gamma)c_4(\beta)\sqrt{\beta^2 + 1}}{(1-\gamma)(x+1)^\gamma}.
\end{aligned}$$

(2) For  $x \geq \frac{2}{\operatorname{Im} \xi_1}$  we have

$$\begin{aligned}
e^{-\operatorname{Im} \xi_1 x} \int_{\frac{1}{\operatorname{Im} \xi_1}}^{\frac{x}{2}} \frac{|e^{-i\xi_1 t} - e^{-i\xi_2 t}|}{(t+1)^{\gamma+1}} dt \\
\leq e^{-\operatorname{Im} \xi_1 \frac{x}{2}} \int_{\frac{1}{\operatorname{Im} \xi_1}}^{\frac{x}{2}} \frac{\left( e^{\operatorname{Im} \xi_1 (t-\frac{x}{2})} + e^{-\operatorname{Im} \xi_1 \frac{x}{2}} \right) dt}{(t+1)^{\gamma+1}} \\
\leq 2e^{-\operatorname{Im} \xi_1 \frac{x}{2}} \int_{\frac{1}{\operatorname{Im} \xi_1}}^{\infty} \frac{dt}{t^{\gamma+1}} \leq \frac{2^{\gamma+1}ec_3(\gamma)}{\gamma(x+2)^\gamma}.
\end{aligned}$$

For  $x < \frac{2}{\operatorname{Im} \xi_1}$  the integral is negative.

(3)

$$e^{-\operatorname{Im} \xi_1 x} \int_{\frac{x}{2}}^x \frac{|e^{-i\xi_1 t} - e^{-i\xi_2 t}|}{(t+1)^{\gamma+1}} dt \leq \int_{\frac{x}{2}}^x \frac{2dt}{(t+1)^{\gamma+1}} < \frac{2^{\gamma+1}}{\gamma(x+2)^\gamma}.$$

Combining these estimates we get

$$\left| e^{i\xi_1 x} \int_0^x \frac{(e^{-i\xi_1 t} - e^{-i\xi_2 t})}{(t+1)^{\gamma+1}} dt \right| < \frac{c_2(\varepsilon, \beta, \gamma)}{(x+1)^\gamma}$$

with

$$\begin{aligned}
c_2(\varepsilon, \beta, \gamma) &:= \frac{2ec_3(\gamma)\sqrt{\beta^2 + 1}}{\varepsilon^2} + \frac{2}{\varepsilon} \\
&+ \frac{\gamma}{\varepsilon} \left( \frac{2^{1-\gamma}ec_3(\gamma)c_4(\beta)\sqrt{\beta^2 + 1}}{1-\gamma} + \frac{2^{\gamma+1}ec_3(\gamma)}{\gamma} + \frac{2^{\gamma+1}}{\gamma} \right).
\end{aligned}$$

This completes the proof of the lemma.  $\square$

Let us continue to estimate  $Q_{21}^I$

$$\begin{aligned}
Q_{21}^I(x, \lambda, \mu) &= \sum_{n=-\infty}^{+\infty} \frac{\hat{c}b_n(\lambda)e^{i\delta+2i\omega+2\pi in\frac{x}{a}}}{2iW(\psi_+(\lambda), \psi_-(\lambda))} e^{i(\frac{2k(\lambda)}{a}-2\omega-\frac{2\pi n}{a})x} \\
&\quad \times \int_0^x \frac{\left( e^{-i(\frac{2k(\lambda)}{a}-2\omega-\frac{2\pi n}{a})t} - e^{-i(\frac{2k(\mu)}{a}-2\omega-\frac{2\pi n}{a})t} \right) dt}{(t+1)^\gamma} \\
&\quad - \sum_{n=-\infty}^{+\infty} \frac{\hat{c}b_n(\lambda)e^{-i\delta-2i\omega+2\pi in\frac{x}{a}}}{2iW(\psi_+(\lambda), \psi_-(\lambda))} e^{i(\frac{2k(\lambda)}{a}+2\omega-\frac{2\pi n}{a})x} \\
&\quad \times \int_0^x \frac{\left( e^{-i(\frac{2k(\lambda)}{a}+2\omega-\frac{2\pi n}{a})t} - e^{-i(\frac{2k(\mu)}{a}+2\omega-\frac{2\pi n}{a})t} \right) dt}{(t+1)^\gamma}.
\end{aligned}$$

Applying Lemma 2 we get

$$(24) \quad |Q_{21}^I(x, \lambda, \mu)| \leq \frac{|c|c_2(\varepsilon(\mu), \beta, \gamma)}{|W(\psi_+(\lambda), \psi_-(\lambda))|} \left( \sum_{n=-\infty}^{+\infty} |\hat{b}_n(\lambda)| \right) \frac{1}{(x+1)^\gamma}.$$

Therefore combining the estimates (22), (24) and (23) the matrix  $Q$  can be estimated as follows

$$\begin{aligned}
\|Q(x, \lambda, \mu)\| &\leq \frac{1}{(x+1)^\gamma} \frac{|c|}{|W(\psi_+(\lambda), \psi_-(\lambda))|} \\
&\quad \times \sqrt{\frac{4}{\varepsilon^2(\mu)} \left( \sum_{n=-\infty}^{+\infty} |b_n(\lambda)| \right)^2 + \left( \frac{2}{\varepsilon(\mu)} + c_2(\varepsilon(\mu), \beta, \gamma) \right)^2 \left( \sum_{n=-\infty}^{+\infty} |\hat{b}_n(\lambda)| \right)^2}.
\end{aligned}$$

Let us estimate now the Fourier coefficients. For  $n \neq 0$  we have:

$$b_n(\lambda) = \frac{1}{a} \int_0^a p_+^2(x, \lambda) e^{-2\pi in\frac{x}{a}} dx = -\frac{a}{4\pi^2 n^2} \int_0^a (p_+^2(x, \lambda))'' e^{-2\pi in\frac{x}{a}} dx.$$

Thus

$$(25) \quad |b_n(\lambda)| \leq \frac{a}{4\pi^2 n^2} \int_0^a |(p_+^2(x, \lambda))''| dx.$$

In terms of the corresponding Bloch solution the second derivative of  $p_+^2$  is

$$\begin{aligned}
(p_+^2(x, \lambda))'' &= 2e^{-\frac{2ik(\lambda)x}{a}} \left( \psi_+''(x, \lambda)\psi_+(x, \lambda) - \frac{2k^2(\lambda)}{a^2}\psi_+^2(x, \lambda) \right. \\
&\quad \left. + (\psi_+'(x, \lambda))^2 - \frac{4ik(\lambda)}{a}\psi_+'(x, \lambda)\psi_+(x, \lambda) \right).
\end{aligned}$$

Let us estimate the norm in  $L_1(0; a)$  of the function  $\psi_+''(\cdot, \lambda)$ . From the equation

$$\psi_+''(x, \lambda) = (q(x) - \lambda)\psi_+(x, \lambda),$$

we see that

$$\|\psi_+''(\cdot, \lambda)\|_{L_1(0;a)} \leq (\|q\|_{L_1(0;a)} + |\lambda|a) \max_{x \in [0;a]} |\psi_+(x, \lambda)|.$$

Since the functions

$$e^{-\frac{ik(\lambda)x}{a}}, \psi_+(x, \lambda), \psi_+'(x, \lambda)$$

are continuous in both variables on the set

$$[0; a] \times U(\beta, \mu)$$

and hence attain their maximums, we have: the integral

$$\int_0^a |(p_+^2(x, \lambda))''| dx$$

is bounded on  $U(\beta, \mu)$ . For  $n=0$ ,

$$b_0(\lambda) = \frac{1}{a} \int_0^a p_+^2(x, \lambda) dx = \frac{1}{a} \int_0^a e^{-2ik(\lambda)\frac{x}{a}} \psi_+^2(x, \lambda) dx$$

and is also bounded. The same argument is valid for  $\hat{b}_n$ . Finally we see that there exists  $c_5(\beta, \mu)$  such that for every  $\lambda \in U(\beta, \mu)$

$$|b_n(\lambda)|, |\hat{b}_n(\lambda)| \leq \frac{c_5(\beta, \mu)}{n^2 + 1}.$$

The Wronskian  $W(\psi_+(\lambda), \psi_-(\lambda))$  does not have zeros in  $U(\beta, \mu)$ . Also in the formula for the derivative of  $Q$ ,

$$Q'(x, \lambda, \mu) = \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))} \begin{pmatrix} 0 & -p_+^2(x, \lambda) \\ p_-^2(x, \lambda) & 0 \end{pmatrix} - \left[ Q(x, \lambda, \mu), \begin{pmatrix} -\frac{ik(\lambda)}{a} & 0 \\ 0 & \frac{ik(\lambda)}{a} \end{pmatrix} \right],$$

the functions  $\pm \frac{k(\lambda)}{a}, \pm c \sin(2\omega x + \delta) p_\pm^2(x, \lambda)$  are bounded for  $(x; \lambda) \in [0; +\infty) \times U(\beta, \mu)$ . Hence there exists  $c_1(\beta, \mu, \gamma)$  such that for every  $\lambda \in U(\beta, \mu)$  and  $x \geq 0$  the following estimates hold

$$\|Q(x, \lambda, \mu)\|, \|Q'(x, \lambda, \mu)\| \leq \frac{c_1(\beta, \mu, \gamma)}{(x+1)^\gamma}.$$

This completes the proof of the theorem.  $\square$



Let us study the properties of the remainder

$$\begin{aligned}
(26) \quad R^{(2)}(x, \lambda, \mu) := & e^{-Q(x, \lambda, \mu)} \left[ \begin{pmatrix} -\frac{ik(\lambda)}{a} & 0 \\ 0 & \frac{ik(\lambda)}{a} \end{pmatrix} \right. \\
& + \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))} \begin{pmatrix} -p_+(x, \lambda)p_-(x, \lambda) & -p_+^2(x, \lambda) \\ p_-^2(x, \lambda) & p_+(x, \lambda)p_-(x, \lambda) \end{pmatrix} \\
& \left. + R^{(1)}(x, \lambda) \right] e^{Q(x, \lambda, \mu)} - \begin{pmatrix} -\frac{ik(\lambda)}{a} & 0 \\ 0 & \frac{ik(\lambda)}{a} \end{pmatrix} \\
& - \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))} \begin{pmatrix} -p_+(x, \lambda)p_-(x, \lambda) & 0 \\ 0 & p_+(x, \lambda)p_-(x, \lambda) \end{pmatrix} \\
& - e^{-Q(x, \lambda, \mu)} (e^{Q(x, \lambda, \mu)})'.
\end{aligned}$$

**Lemma 3.** *The remainder  $R^{(2)}$  given by (26) possesses the following properties:*

(1)  $R^{(2)} \in L_1(0; \infty)$  and the integral

$$\int_0^\infty \|R^{(2)}(x, \lambda, \mu)\| dx$$

converges uniformly with respect to  $\lambda \in U(\beta, \mu)$ .

(2)

$$\begin{aligned}
(27) \quad (R^{(2)}(x, \mu, \mu))_{21} &= \overline{(R^{(2)}(x, \mu, \mu))_{12}}, \\
(R^{(2)}(x, \mu, \mu))_{22} &= (R^{(2)}(x, \mu, \mu))_{11}.
\end{aligned}$$

**PROOF.** The first assertion follows directly from Theorem 2.

The property of matrices from the second assertion is preserved under summation and multiplication of such matrices as well as taking the inverse. We can see from (11) and (18) that  $R^{(1)}(x, \mu)$  and  $Q(x, \mu, \mu)$  possess this conjugation property. Therefore

$$Q'(x, \mu, \mu), e^{Q(x, \mu, \mu)}, (e^{Q(x, \mu, \mu)})'$$

and finally  $R^{(2)}(x, \mu, \mu)$  (from (26)) also possess this property. It should be taken into account that  $W(\psi_+(\mu), \psi_-(\mu))$  is pure imaginary.  $\square$

Let us denote

$$\nu(x, \lambda) := -\frac{ik(\lambda)}{a} - \frac{c \sin(2\omega x + \delta) p_+(x, \lambda) p_-(x, \lambda)}{(x+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))}.$$

Finally we obtain a system of the Levinson form:

$$(28) \quad \tilde{v}'(x) = \left[ \begin{pmatrix} \nu(x, \lambda) & 0 \\ 0 & -\nu(x, \lambda) \end{pmatrix} + R^{(2)}(x, \lambda, \mu) \right] \tilde{v}(x).$$

#### 4. A Levinson-type theorem for $2 \times 2$ systems

In this section, we prove two statements that give a uniform estimate and asymptotics of solutions to certain  $2 \times 2$  differential systems. The approach is the same as for the Levinson theorem [8], but the difference is that we are interested in properties of solution with a given initial condition.

Consider the system

$$(29) \quad u_1'(x) = \left[ \begin{pmatrix} \lambda(x) & 0 \\ 0 & -\lambda(x) \end{pmatrix} + R(x) \right] u_1(x)$$

for  $x \geq 0$ , where  $u_1(x)$  is a two-dimensional vector function and  $R(x)$  is a  $2 \times 2$  matrix with complex entries.

**Lemma 4.** *Assume that*

$$(30) \quad \int_0^\infty \|R(t)\| dt < \infty.$$

*and that there exists a constant  $M$  such that for every  $x \leq y$  it holds*

$$\int_x^y \operatorname{Re} \lambda(t) dt \geq -M.$$

*Then every solution  $u_1$  to (29) satisfies the estimate*

$$(31) \quad \|u_1(x)\| \leq \|u_1(0)\| e^{\int_0^x \operatorname{Re} \lambda(t) dt} \sqrt{1 + e^{4M}} e^{\sqrt{1 + e^{4M}} \int_0^\infty \|R(t)\| dt}.$$

**PROOF.** First transform the system (29) by variation of parameters. Denote

$$\Lambda(x) := \begin{pmatrix} \lambda(x) & 0 \\ 0 & -\lambda(x) \end{pmatrix}$$

and take

$$(32) \quad u_1(x) = e^{\int_0^x \Lambda(t) dt} u_2(x), \text{ or } u_2(x) := e^{-\int_0^x \Lambda(t) dt} u_1(x).$$

After substitution (29) becomes

$$(33) \quad u_2'(x) = e^{-\int_0^x \Lambda(t) dt} R(x) u_1(x).$$

Integrating this from 0 to  $x$  and returning back to the function  $u_1$  on the left-hand side we get

$$(34) \quad u_1(x) = e^{\int_0^x \Lambda(t) dt} u_1(0) + \int_0^x e^{\int_t^x \Lambda(s) ds} R(t) u_1(t) dt.$$

Now multiply this expression by  $e^{-\int_0^x \Lambda(s) ds}$  and denote

$$(35) \quad u_3(x) := e^{-\int_0^x \Lambda(t) dt} u_1(x).$$

We get the following equation for  $u_3$  considered in  $L_\infty(0, \infty); \mathbb{C}^2$   
(36)

$$u_3(x) = \begin{pmatrix} 1 & 0 \\ 0 & e^{-2 \int_0^x \lambda(s) ds} \end{pmatrix} u_1(0) + \int_0^x \begin{pmatrix} 1 & 0 \\ 0 & e^{-2 \int_t^x \lambda(s) ds} \end{pmatrix} R(t) u_3(t) dt.$$

The norm of the operator  $V$ ,

$$V : u \mapsto \int_0^x \begin{pmatrix} 1 & 0 \\ 0 & e^{-2 \int_t^x \lambda(s) ds} \end{pmatrix} R(t) u(t) dt$$

is bounded by

$$\|V\| \leq \sqrt{1 + e^{4M}} \int_0^\infty \|R(t)\| dt$$

and the norm of the  $j$ -th power is bounded by

$$\|V^j\| \leq \frac{(\sqrt{1 + e^{4M}} \int_0^\infty \|R(t)\| dt)^j}{j!}.$$

Hence

$$u_3(x) = (I - V)^{-1} \begin{pmatrix} 1 & 0 \\ 0 & e^{-2 \int_0^x \lambda(s) ds} \end{pmatrix} u_1(0)$$

and

$$\|u_3\|_{L_\infty((0; \infty), \mathbb{C}^2)} \leq \exp \left( \sqrt{1 + e^{4M}} \int_0^\infty \|R(t)\| dt \right) \sqrt{1 + e^{4M}} \|u_1(0)\|.$$

Returning to  $u_1$ , we arrive at the estimate (31).  $\square$

The second lemma states the asymptotics of the solution.

**Lemma 5.** *Let that all conditions of Lemma 4 be satisfied, then the following asymptotics hold:*

(1) *If*

$$(37) \quad \int_0^\infty \operatorname{Re} \lambda(t) dt < +\infty,$$

*then every solution  $u_1$  of (29) has the following asymptotics:*

$$u_1(x) = \begin{pmatrix} e^{\int_0^x \lambda(s) ds} & 0 \\ 0 & e^{-\int_0^x \lambda(s) ds} \end{pmatrix} [u_1(0) + \int_0^\infty \begin{pmatrix} e^{-\int_0^t \lambda(s) ds} & 0 \\ 0 & e^{\int_0^t \lambda(s) ds} \end{pmatrix} R(t) u_1(t) dt + o(1)] \quad \text{as } x \rightarrow \infty.$$

(2) *If*

$$(38) \quad \int_0^\infty \operatorname{Re} \lambda(t) dt = +\infty,$$

then every solution  $u_1$  of (29) has the following asymptotics:

$$u_1(x) = e^{\int_0^x \lambda(s) ds} \left[ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} (u_1(0) + \int_0^\infty e^{-\int_0^t \lambda(s) ds} R(t) u_1(t) dt) + o(1) \right] \text{ as } x \rightarrow \infty.$$

PROOF. Asymptotics 1. Consider the function  $u_2$  given by (32) and integrate (33):

$$(39) \quad u_2(x) = u_1(0) + \int_0^x e^{-\int_0^t \Lambda(s) ds} R(t) u_1(t) dt.$$

Since for every  $x \leq y$  we have the estimate

$$\begin{aligned} \int_x^y \operatorname{Re} \lambda(s) ds &\leq \int_x^y |\operatorname{Re} \lambda(s)| ds \\ &\leq \int_0^\infty |\operatorname{Re} \lambda(s)| ds \leq \int_0^\infty \operatorname{Re} \lambda(s) ds + 2M, \end{aligned}$$

the exponent under the integral in (39) is bounded. The solution  $u_1(t)$  is also bounded in this case due to Lemma 4. Hence the integral in (39) converges as  $x \rightarrow \infty$  and there exists

$$\lim_{x \rightarrow \infty} u_2(x) = u_1(0) + \int_0^\infty e^{-\int_0^t \Lambda(s) ds} R(t) u_1(t) dt.$$

Returning to  $u_1$  we obtain the answer.

Asymptotics 2. Consider the function  $u_3$  given by (35) and the corresponding equation (36). It follows from Lemma 4 that  $u_3(t)$  is bounded, and hence Lebesgue's dominated convergence theorem implies that the following limit exists

$$\lim_{x \rightarrow \infty} u_3(x) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \left[ u_1(0) + \int_0^\infty R(t) u_3(t) dt \right].$$

This is equivalent to the announced asymptotics for  $u_1$ .  $\square$

## 5. Asymptotics for the solution $\varphi$ and Weyl-Titchmarsh type formula

In this section, we obtain the asymptotics for the solution  $\varphi_\alpha(x, \lambda)$  and prove the Weyl-Titchmarsh type formula for the operator  $\mathcal{L}_\alpha$ . Consider the set

$$U(\beta) := \bigcup_{\mu \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, \lambda_n^+, \lambda_n^-, n \geq 0\}} U(\beta, \mu)$$

that belongs to  $\overline{\mathbb{C}_+}$  and contains

$$\sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, \lambda_n^+, \lambda_n^-, n \geq 0\}$$

as a part of its boundary. The number  $\beta$  is arbitrary here.

**Theorem 3.** *Let  $\frac{2a\omega}{\pi} \notin \mathbb{Z}$  and  $q_1 \in L_1(\mathbb{R}_+)$ , then the solution  $\varphi_\alpha$  of the Cauchy problem*

$$\begin{aligned} -\varphi_\alpha''(x, \lambda) + \left( q(x) + \frac{c \sin(2\omega x + \delta)}{(x+1)^\gamma} + q_1(x) \right) \varphi_\alpha(x, \lambda) &= \lambda \varphi_\alpha(x, \lambda), \\ \varphi_\alpha(0, \lambda) &= \sin \alpha, \\ \varphi_\alpha'(0, \lambda) &= \cos \alpha \end{aligned}$$

has the following asymptotics. For every  $\lambda \in U(\beta)$  there exists  $A_\alpha(\lambda)$  such that

(1) *If  $\lambda \in \mathbb{C}_+ \cap U(\beta)$ , then*

$$\begin{aligned} \varphi_\alpha(x, \lambda) &= A_\alpha(\lambda) \psi_-(x, \lambda) + o\left(e^{Im \ k(\lambda) \frac{x}{a}}\right), \\ \varphi_\alpha'(x, \lambda) &= A_\alpha(\lambda) \psi'_-(x, \lambda) + o\left(e^{Im \ k(\lambda) \frac{x}{a}}\right) \end{aligned}$$

as  $x \rightarrow \infty$ .

(2) *If  $\lambda \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, \lambda_n^+, \lambda_n^-, n \geq 0\}$ , then*

$$\begin{aligned} \varphi_\alpha(x, \lambda) &= A_\alpha(\lambda) \psi_-(x, \lambda) + \overline{A_\alpha(\lambda)} \psi_+(x, \lambda) + o(1), \\ \varphi_\alpha'(x, \lambda) &= A_\alpha(\lambda) \psi'_-(x, \lambda) + \overline{A_\alpha(\lambda)} \psi'_+(x, \lambda) + o(1) \end{aligned}$$

as  $x \rightarrow \infty$ .

The function  $A_\alpha$  is analytic in the interior of  $U(\beta)$  and has boundary values on

$$\sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, \lambda_n^+, \lambda_n^-, n \geq 0\}.$$

PROOF. We are going to omit the index  $\alpha$  since the value of the boundary parameter is fixed throughout this proof. According to (8) and (10) we write

$$(40) \quad \begin{pmatrix} \varphi(x) \\ \varphi'(x) \end{pmatrix} = \begin{pmatrix} \psi_-(x, \lambda) & \psi_+(x, \lambda) \\ \psi'_-(x, \lambda) & \psi'_+(x, \lambda) \end{pmatrix} \begin{pmatrix} e^{ik(\lambda) \frac{x}{a}} & 0 \\ 0 & e^{-ik(\lambda) \frac{x}{a}} \end{pmatrix} v_\varphi(x, \lambda).$$

This is the definition of  $v_\varphi$ , a solution of (12) corresponding to  $\varphi$ . Let us fix the point

$$\mu \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, \lambda_n^+, \lambda_n^-, n \geq 0\}$$

and consider  $\lambda \in U(\beta, \mu)$ . The function

$$\tilde{v}_\varphi(x, \lambda, \mu) := e^{-Q(x, \lambda, \mu)} v_\varphi(x, \lambda),$$

is a solution to (28) corresponding to  $\varphi$ . Let us see that conditions of Lemma 4 are satisfied for the system (28) uniformly with respect to  $\lambda \in U(\beta, \mu)$ . First of all we have estimate (30) from Lemma 3 and

$$\operatorname{Re} \nu(x, \lambda) = \frac{\operatorname{Im} k(\lambda)}{a} - \operatorname{Re} \left( \frac{c \sin(2\omega x + \delta) p_+(x, \lambda) p_-(x, \lambda)}{(x+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))} \right).$$

Estimating the second term in the same way as in Theorem 2 we have:

$$\begin{aligned} \left| \int_x^y \operatorname{Re} \frac{c \sin(2\omega t + \delta) p_+(t, \lambda) p_-(t, \lambda)}{(t+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))} dt \right| &\leq \frac{|c|a}{\pi |W(\psi_+(\lambda), \psi_-(\lambda))|} \\ &\times \left( \sum_{n=-\infty}^{\infty} |\tilde{b}_n(\lambda)| \left( \frac{1}{\left| \frac{2a\omega}{\pi} + 2n \right|} + \frac{1}{\left| \frac{2a\omega}{\pi} - 2n \right|} \right) \right) \frac{1}{(x+1)^\gamma}, \end{aligned}$$

where

$$\tilde{b}_n(\lambda) := \frac{1}{a} \int_0^a p_+(x, \lambda) p_-(x, \lambda) e^{-2\pi i n \frac{x}{a}} dx$$

are Fourier coefficients for  $p_+(\cdot, \lambda) p_-(\cdot, \lambda)$ . Analogously to (25) we have:

$$|\tilde{b}_n(\lambda)| \leq \frac{a}{4\pi^2 n^2} \int_0^a |(\psi_+(x, \lambda) \psi_-(x, \lambda))''| dx.$$

So there exists  $c_6(\beta, \mu)$  such that for every  $\lambda \in U(\beta, \mu)$  and  $n \neq 0$

$$|\tilde{b}_n(\lambda)| \leq \frac{c_6(\beta, \mu)}{n^2},$$

while

$$|\tilde{b}_0(\lambda)| \leq c_6(\beta, \mu).$$

Eventually there exists  $c_7(\beta, \mu)$  such that

$$\left| \int_x^y \operatorname{Re} \frac{c \sin(2\omega t + \delta) p_+(t, \lambda) p_-(t, \lambda)}{(t+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))} dt \right| \leq c_7(\beta, \mu)$$

for every  $0 \leq x \leq y$  and  $\lambda \in U(\beta, \mu)$ . Thus we can take

$$M(\lambda) \equiv c_7(\beta, \mu)$$

for these values of  $\lambda$ . Lemma 4 gives the estimate

$$(41) \quad \|\tilde{v}_\varphi(x, \lambda, \mu)\| \leq \|\tilde{v}_\varphi(0, \lambda, \mu)\| e^{\operatorname{Im} k(\lambda) \frac{x}{a}} c_8(\beta, \mu),$$

where

$$\begin{aligned} c_8(\beta, \mu) &:= \sqrt{1 + e^{4c_7(\beta, \mu)}} \\ &\times \exp \left( \sqrt{1 + e^{4c_7(\beta, \mu)}} \max_{\lambda \in U(\beta, \mu)} \int_0^\infty \|R^{(2)}(t, \lambda)\| dt \right). \end{aligned}$$

Conditions of Lemma 5 are also satisfied: (37) holds for  $\lambda \in \mathbb{R} \cap U(\beta, \mu)$  and (38) holds for  $\lambda \in \mathbb{C}_+ \cap U(\beta, \mu)$ . So Lemma 5 gives the following asymptotics:

- for  $\lambda \in \mathbb{C}_+ \cap U(\beta, \mu)$ ,

$$\begin{aligned} \tilde{v}_\varphi(x, \lambda, \mu) = & e^{-ik(\lambda)\frac{x}{a} - \int_0^x \frac{c \sin(2\omega t + \delta) p_+(t, \lambda) p_-(t, \lambda) dt}{(t+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))}} \left[ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} (\tilde{v}_\varphi(0, \lambda, \mu) \right. \\ & \left. + \int_0^\infty e^{ik(\lambda)\frac{t}{a} + \int_0^t \frac{c \sin(2\omega s + \delta) p_+(s, \lambda) p_-(s, \lambda) ds}{(s+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))}} R^{(2)}(t, \lambda, \mu) \tilde{v}_\varphi(t, \lambda, \mu) dt \right) + o(1) \Big], \end{aligned}$$

- for  $\lambda = \mu$ ,

$$(42) \quad \begin{aligned} \tilde{v}_\varphi(x, \mu, \mu) = & \begin{pmatrix} e^{-ik(\mu)\frac{x}{a} - \int_0^x \frac{c \sin(2\omega t + \delta) p_+(t, \mu) p_-(t, \mu) dt}{(t+1)^\gamma W(\psi_+(\mu), \psi_-(\mu))}} & 0 \\ 0 & e^{ik(\mu)\frac{x}{a} + \int_0^x \frac{c \sin(2\omega t + \delta) p_+(t, \mu) p_-(t, \mu) dt}{(t+1)^\gamma W(\psi_+(\mu), \psi_-(\mu))}} \end{pmatrix} \\ & \times \left[ \tilde{v}_\varphi(0, \mu, \mu) + \int_0^\infty \begin{pmatrix} e^{ik(\mu)\frac{t}{a} + \int_0^t \frac{c \sin(2\omega s + \delta) p_+(s, \mu) p_-(s, \mu) ds}{(s+1)^\gamma W(\psi_+(\mu), \psi_-(\mu))}} & 0 \\ 0 & e^{-ik(\mu)\frac{t}{a} - \int_0^t \frac{c \sin(2\omega s + \delta) p_+(s, \mu) p_-(s, \mu) ds}{(s+1)^\gamma W(\psi_+(\mu), \psi_-(\mu))}} \end{pmatrix} \right. \\ & \left. \times R^{(2)}(t, \mu, \mu) \tilde{v}_\varphi(t, \mu, \mu) dt + o(1) \right]. \end{aligned}$$

Since  $Q(x, \lambda, \mu) = O\left(\frac{1}{(x+1)^\gamma}\right)$ , we can denote for  $\lambda \in U(\beta, \mu)$ :

$$(43) \quad \begin{aligned} A(\lambda, \mu) := & \left\langle \begin{pmatrix} 1 \\ 0 \end{pmatrix}, e^{-\int_0^\infty \frac{c \sin(2\omega t + \delta) p_+(t, \lambda) p_-(t, \lambda) dt}{(t+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))}} \left[ e^{-Q(0, \lambda, \mu)} v_\varphi(0, \lambda) \right. \right. \\ & \left. \left. + \int_0^\infty e^{ik(\lambda)\frac{t}{a} + \int_0^t \frac{c \sin(2\omega s + \delta) p_+(s, \lambda) p_-(s, \lambda) ds}{(s+1)^\gamma W(\psi_+(\lambda), \psi_-(\lambda))}} R^{(2)}(t, \lambda, \mu) e^{Q(t, \lambda, \mu)} v_\varphi(t, \lambda) dt \right] \right\rangle \end{aligned}$$

(where  $\langle \cdot, \cdot \rangle$  stands for the scalar product in  $\mathbb{C}^2$ ) and have:

$$(43) \quad \lim_{x \rightarrow \infty} v_\varphi(x, \lambda) e^{ik(\lambda)\frac{x}{a}} = \begin{pmatrix} A(\lambda, \mu) \\ 0 \end{pmatrix}.$$

From this we see that the coefficient  $A(\lambda, \mu)$  does not depend on  $\mu$ , so we will denote it by  $A(\lambda)$ . Relation (40) can be written as

$$(44) \quad v_\varphi(x, \lambda) = \frac{1}{W(\psi_+(\lambda), \psi_-(\lambda))} \begin{pmatrix} \psi'_+(x, \lambda) \varphi(x, \lambda) - \psi_+(x, \lambda) \varphi'(x, \lambda) \\ \varphi'(x, \lambda) \psi_-(x, \lambda) - \varphi(x, \lambda) \psi'_-(x, \lambda) \end{pmatrix},$$

so  $v_\varphi(x, \cdot)$  is analytic in  $\mathbb{C}_+$  and continuous up to

$$\sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, n \geq 0\}.$$

From the estimate (41) and properties of  $Q(x, \lambda, \mu)$  and  $R^{(2)}(x, \lambda, \mu)$  given by Theorem 2 and Lemma 3 it follows that  $A(\lambda)$  is continuous in

$U(\beta, \mu)$  and analytic in its interior. Thus  $A$  is analytic in the interior of  $U(\beta)$  having non-tangential boundary limits on

$$\sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, \lambda_n^+, \lambda_n^-, n \geq 0\}.$$

that coincide with its values on this set.

The solution  $\varphi(x, \lambda)$  and its derivative are real if  $\lambda$  is real. Thus (44) shows that the upper and the lower components of the vector  $v_\varphi(x, \lambda)$  are complex conjugate for  $\lambda \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, n \geq 0\}$ . This property is preserved if we multiply the vector by a matrix  $X$  such that

$$X_{21} = \overline{X_{12}}, \quad X_{22} = \overline{X_{11}},$$

like (27). It follows from Lemma 3 that the upper and the lower components of the vectors in the equality (42) are complex conjugate to each other. Hence for  $\lambda = \mu$  we have

$$(45) \quad v_\varphi(x, \mu) = \left( \begin{array}{c} \frac{A(\mu)e^{-ik(\mu)\frac{x}{a}}}{A(\mu)e^{ik(\mu)\frac{x}{a}}} \end{array} \right) + o(1) \text{ as } x \rightarrow \infty.$$

The asymptotics of the solution  $\varphi$  and its derivative follows from (40), (43) and (45).  $\square$

Using the obtained asymptotics both on the spectrum and in  $\mathbb{C}_+$  we now prove the Weyl-Titchmarsh type formula.

**Theorem 4.** *Let  $\frac{2a\omega}{\pi} \notin \mathbb{Z}$  and  $q_1 \in L_1(\mathbb{R}_+)$ , then for almost all  $\lambda \in \sigma(\mathcal{L}_{per})$  the spectral density of the operator  $\mathcal{L}_\alpha$ , defined by (1), is given by*

$$\rho'_\alpha(\lambda) = \frac{1}{2\pi |W(\psi_+(\lambda), \psi_-(\lambda))| |A_\alpha(\lambda)|^2},$$

where  $A_\alpha$  is the same as in Theorem 3.

**PROOF.** In addition to  $\varphi_\alpha$  consider another one solution of (7), to be denoted by  $\theta_\alpha := \varphi_{\alpha+\frac{\pi}{2}}$ , satisfying the initial conditions

$$\theta_\alpha(0, \lambda) = \cos \alpha, \quad \theta'_\alpha(0, \lambda) = -\sin \alpha.$$

The Wronskian of  $\varphi_\alpha$  and  $\theta_\alpha$  is equal to one. Theorem 3 yields for  $\lambda \in U(\beta) \cap \mathbb{C}_+$ ,

$$\theta_\alpha(x, \lambda) = A_{\alpha+\frac{\pi}{2}}(\lambda)\psi_-(x, \lambda) + o(e^{\text{Im } k(\lambda)\frac{x}{a}}) \text{ as } x \rightarrow \infty.$$

Since the operator  $\mathcal{L}_\alpha$  is in the limit point case, the combination

$$\theta_\alpha + m_\alpha \varphi_\alpha$$

belongs to  $L_2(0, \infty)$  (where  $m_\alpha$  is the Weyl function for  $\mathcal{L}_\alpha$ ). It has the asymptotics

$$\theta_\alpha(x, \lambda) + m_\alpha(\lambda)\varphi_\alpha(x, \lambda) = (A_{\alpha+\frac{\pi}{2}}(\lambda) + m_\alpha A_\alpha(\lambda))\psi_-(x, \lambda) + o(e^{\text{Im } k(\lambda)\frac{x}{a}}).$$



Therefore

$$m_\alpha(\lambda) = -\frac{A_{\alpha+\frac{\pi}{2}}(\lambda)}{A_\alpha(\lambda)}$$

for  $\lambda \in U(\beta) \cap \mathbb{C}_+$  and

$$m_\alpha(\lambda + i0) = -\frac{A_{\alpha+\frac{\pi}{2}}(\lambda)}{A_\alpha(\lambda)}$$

for  $\lambda \in \sigma(\mathcal{L}_{per}) \setminus \{\lambda_n, \mu_n, \lambda_n^+, \lambda_n^-, n \geq 0\}$ . It follows from the subordinacy theory [10] that the spectrum of  $\mathcal{L}_\alpha$  on this set is purely absolutely continuous and

$$(46) \quad \rho'_\alpha(\lambda) = \frac{1}{\pi} \operatorname{Im} m_\alpha(\lambda + i0) = \frac{A_\alpha(\lambda) \overline{A_{\alpha+\frac{\pi}{2}}(\lambda)} - \overline{A_\alpha(\lambda)} A_{\alpha+\frac{\pi}{2}}(\lambda)}{2\pi i |A_\alpha(\lambda)|^2}.$$

Theorem 3 yields for these values of  $\lambda$ :

$$\begin{aligned} \theta_\alpha(x, \lambda) &= A_{\alpha+\frac{\pi}{2}}(\lambda) \psi_-(x, \lambda) + \overline{A_{\alpha+\frac{\pi}{2}}(\lambda)} \psi_+(x, \lambda) + o(1), \\ \theta'_\alpha(x, \lambda) &= A_{\alpha+\frac{\pi}{2}}(\lambda) \psi'_-(x, \lambda) + \overline{A_{\alpha+\frac{\pi}{2}}(\lambda)} \psi'_+(x, \lambda) + o(1), \end{aligned}$$

as  $x \rightarrow \infty$ . Substituting these asymptotics and the asymptotics of  $\varphi_\alpha$  and  $\varphi'_\alpha$  into the expression for the Wronskian we get:

$$1 = (\overline{A_\alpha(\lambda)} A_{\alpha+\frac{\pi}{2}}(\lambda) - A_\alpha(\lambda) \overline{A_{\alpha+\frac{\pi}{2}}(\lambda)}) W(\psi_+(\lambda), \psi_-(\lambda))$$

(the term  $o(1)$  cancels, since both sides are independent of  $x$ ). Combining with (46) we have

$$\begin{aligned} \rho'_\alpha(\lambda) &= \frac{1}{-2\pi i W(\psi_+(\lambda), \psi_-(\lambda)) |A_\alpha(\lambda)|^2} \\ &= \frac{1}{2\pi |W(\psi_+(\lambda), \psi_-(\lambda))| |A_\alpha(\lambda)|^2}, \end{aligned}$$

which completes the proof.  $\square$

## 6. Acknowledgements

The second author expresses his deep gratitude to Professor S.N. Naboko for his constant attention to this work and for many fruitful discussions on the subject and also to the Mathematics Department of Lund Institute of Technology for financial support and hospitality. The work was supported by grants RFBR-09-01-00515-a, INTAS-05-1000008-7883 and Swedish Research Council 80525401.

## References

- [1] S. Albeverio. On bound states in the continuum of  $N$ -body systems and the virial theorem. *Ann. Physics*, 71:167–276, 1972.
- [2] H. Behncke. Absolute continuity of hamiltonians with von Neumann Wigner Potentials I. *Proceedings of the American Mathematical Society*, 111:373–384, 1991.
- [3] H. Behncke. Absolute continuity of hamiltonians with von Neumann Wigner potentials II. *Manuscripta Mathematica*, 71(1):163–181, 1991.
- [4] H. Behncke. The  $m$ -function for Hamiltonians with Wigner-von Neumann potentials. *Journal of Mathematical Physics*, 35(4):1445–1462, 1994.
- [5] B.M. Brown, M.S.P. Eastham, and D.K.R. McCormack. Absolute continuity and spectral concentration for slowly decaying potentials. *Journal of Computational and Applied Mathematics*, 94:181–197, 1998. arXiv:math/9805025v1.
- [6] V.S. Buslaev and V.B. Matveev. Wave operators for the Schrödinger equation with a slowly decreasing potential. *Theoretical and Mathematical Physics*, 2(3):266–274, 1970.
- [7] F. Capasso, C. Sirtori, J. Faist, D.L. Sivco, S.N.G. Chu, and A.Y. Cho. Observation of an electronic bound state above a potential well. *Nature*, 358:565–567, 1992.
- [8] E.A. Coddington and N. Levinson. *Theory of ordinary differential equations*. McGraw-Hill, New York, 1955.
- [9] M.S.P. Eastham. *The spectral theory of periodic differential equations*. Edinburgh, 1973.
- [10] D.J. Gilbert and D.B. Pearson. On subordinacy and analysis of the spectrum of one-dimensional Schrödinger operators. *Journal of mathematical analysis and applications*, 128(1):30–56, 1987.
- [11] W.A. Harris and D.A. Lutz. Asymptotic integration of adiabatic oscillators. *J. Math. Anal. Appl.*, 51:76–93, 1975.
- [12] D.B. Hinton, M. Klaus, and J.K. Shaw. Embedded half-bound states for potentials of Wigner-von Neumann type. *Proceedings of the London Mathematical Society*, 3(3):607–646, 1991.
- [13] M. Klaus. Asymptotic behavior of Jost functions near resonance points for Wigner-von Neumann type potentials. *Journal of Mathematical Physics*, 32:163–174, 1991.
- [14] P. Kurasov. Zero-range potentials with internal structures and the inverse scattering problem. *Letters in Mathematical Physics*, 25(4):287–297, 1992.
- [15] P. Kurasov. Scattering matrices with finite phase shift and the inverse scattering problem. *Inverse Problems*, 12(3):295–307, 1996.
- [16] P. Kurasov and S. Naboko. Wigner-von Neumann perturbations of a periodic potential: spectral singularities in bands. *Mathematical Proceedings of the Cambridge Philosophical Society*, 142(01):161–183, 2007.
- [17] V.B. Matveev. Wave operators and positive eigenvalues for a Schrödinger equation with oscillating potential. *Theoretical and Mathematical Physics*, 15(3):574–583, 1973.
- [18] V.B. Matveev and M.M. Skriganov. Scattering problem for radial Schrödinger equation with a slowly decreasing potential. *Theoretical and Mathematical Physics*, 10(2):156–164, 1972.

- [19] J. von Neumann and E.P. Wigner. Über merkwürdige diskrete Eigenwerte. *Z. Phys*, 30:465–467, 1929.

DEPARTMENT OF MATHEMATICS, LUND INSTITUTE OF TECHNOLOGY, 221  
00 LUND, SWEDEN,  
*E-mail address:* `kurasov@maths.lth.se`

DEPARTMENT OF MATHEMATICAL PHYSICS, INSTITUTE OF PHYSICS, ST. PE-  
TERSBERG UNIVERSITY, ULIANOVSKAIA 1, ST. PETERGOFF, ST. PETERSBURG,  
RUSSIA, 198904  
*E-mail address:* `sergey_simonov@mail.ru`