Asymptotics of eigenvalues of the operator describing Aharonov-Bohm effect combined with homogeneous magnetic field coupled with a strong $\delta$-interaction on a loop

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Abstract

We investigate the two-dimensional magnetic operator $H_{c_0,B,\beta} = (-i\nabla - A)^2 - \beta \delta(-\Gamma)$, where $\Gamma$ is a smooth loop. The vector potential has the form $A = c_0 \left( \frac{-y}{x^2+y^2}; \frac{x}{x^2+y^2} \right) + \frac{B}{2} \left( -y; x \right); B > 0$, $c_0 \in [0; 1]$. The asymptotics of negative eigenvalues of $H_{c_0,B,\beta}$ for $\beta \to +\infty$ is found. We also prove that for large enough positive value of $\beta$ the system exhibits persistent currents.

1 Introduction

In the presence of a static magnetic field, a single isolated normal-metal loop is predicted to carry an equilibrium current, which is periodic in the magnetic flux $\Phi$ threading the loop. This current arises due to the boundary conditions imposed by the doubly connected nature of the loop. As a consequence of these boundary conditions, the free energy $E$ and the thermodynamic current $I(\Phi) = \frac{\partial E}{\partial \Phi}$ are periodic in $\Phi$, with a fundamental period $\Phi_0 = \hbar/e$. In recent papers Exner and Yoshitomi have derived an asymptotic formula showing that if the $\delta$–coupling is
strong or in a homogeneous magnetic field \( B \) perpendicular to the plane, the negative eigenvalues approach those of the ideal model in which the geometry of \( \Gamma \) is taken into account by means of an effective curvature-induced potential. In [5], the same result is proved when the vector potential is the Aharonov one.

The purpose of this paper is to prove the same result when the electron is subject to a Bohm-Aharonov effect in the plane on the background of a homogeneous magnetic field. As a consequence of this result, we prove that the system exhibits persistent currents.

2 The model and the results

In this section, we study the magnetic operator in \( L^2(\mathbb{R}^2) \) with an attractive \( \delta \)-interaction applied to a loop. We use the gauge field \( A = c_0 \left( -\frac{y}{x^2+y^2}; \frac{x}{x^2+y^2} \right) + \frac{B}{2} \left( -y; x \right) \).

Let \( \Gamma : [0, L] \ni s \mapsto (\Gamma_1(s), \Gamma_2(s)) \in \mathbb{R}^2 \) be the closed counter-clockwise \( C^4 \) Jordan curve which is parametrized by its arc length. Given \( \beta > 0 \) and \((c_0, B) \in ]0, 1[ \times ]0, \infty[\), we define the quadratic form

\[
q_{c_0, B, \beta}(f; f) = \left\| (-i\partial_x + \frac{c_0 y}{x^2+y^2} + \frac{B}{2} y) f \right\|^2_{L^2(\mathbb{R}^2)} + \left\| (-i\partial_y - \frac{c_0 x}{x^2+y^2} - \frac{B}{2} x) f \right\|^2_{L^2(\mathbb{R}^2)} - \beta \int_{\Gamma} |f(x)|^2 ds
\]

with the domain \( H^1(\mathbb{R}^2) \), where \( \partial_x \equiv \frac{\partial}{\partial x} \), and the norm refers to \( L^2(\mathbb{R}^2) \).

Let us denote by \( H_{c_0, B, \beta} \) the self-adjoint operator associated to the form \( q_{c_0, B, \beta}(,): \)

\[
H_{c_0, B, \beta} = (-i\nabla - A)^2 - \beta \delta(-, - \Gamma).
\]

Our main goal is to study, as in [4], the asymptotic behaviour of the negative eigenvalues of \( H_{c_0, B, \beta} \) as \( \beta \to +\infty \).

Let \( \gamma : \mathbb{R} \to \mathbb{R} \) be the signed curvature of \( \Gamma \), i.e.

\[
\gamma(s) := \left( \Gamma''_1 \Gamma'_2 - \Gamma''_2 \Gamma'_1 \right)(s).
\]

Next we need a comparison operator on the curve

\[
S_{c_0, B} = -\frac{d^2}{ds^2} - \frac{1}{4} \gamma(s)^2 \in L^2((0; L)],
\]

with the domain

\[
P_{c_0, B} = \{ u \in H^2([0; L[); u^{(k)}(L) = u^{(k)}(0); k = 1, 2 \}.
\]

For \( j \in \mathbb{N} \), we denote by \( \mu_j(c_0, B) \) the \( j \)-th eigenvalue of the operator \( S_{c_0, B} \) counted with multiplicity. This allows us to formulate our main result, and his proof follows in the same way as in [4]:
Theorem 2.1 Let $n$ be an arbitrary integer and $I$ be a nonempty compact subset of $]0, 1[ \times ]0, \infty[$. Then there exists $\beta(n, I)$ such that $\# \{\sigma_d(H_{c_0,B,\beta}) \cap ]-\infty, 0[\} \geq n$ for $\beta \geq \beta(n, I)$ and $(c_0, B) \in I$.

For $\beta \geq \beta(n, I)$ and $(c_0, B) \in I$ we denote by $\lambda_n(c_0, B, \beta)$ the $n^{th}$ eigenvalue of $H_{c_0,B,\beta}$ counted with multiplicity.

Then $\lambda_n(c_0, B, \beta)$ admits an asymptotic expansion of the form

\[ \lambda_n(c_0, B, \beta) = - \frac{1}{4} \beta^2 + \mu_n(c_0, B) + O(\beta^{-1} \ln \beta) \quad \text{as} \quad \beta \to +\infty; \]

where the error term is uniform with respect to $(c_0, B) \in I$.

The existence of persistent currents is given by the consequence of the following result.

Corollary 2.1 Let $n \in \mathbb{N}$. Then there exists a constant $\beta_1(n, I) > 0$ such that the function $\lambda_n(., ., \beta)$ is not constant for $\beta > \beta_1(n, I)$.

Since the spectral properties of $H_{c_0,B,\beta}$ are cleary invariant with respect to Euclidean transformation of the plane, we may assume without any loss of generality that the curve $\Gamma$ parametrized in the following way:

\[ \Gamma_1(s) = \Gamma_1(0) + \int_0^s \cos H(t)dt \quad \Gamma_2(s) = \Gamma_2(0) + \int_0^s \sin H(t)dt \]

where $H(t) \equiv - \int_0^t \gamma(u) du$. Let $\Psi_a$ be the map

\[ \Psi_a : [0, L) \times (-a, a) \ni (s, u) \mapsto (\Gamma_1(s) - u \Gamma'_2(s), \Gamma_2(s) + u \Gamma'_1(s)) \in \mathbb{R}^2. \]

From [3] we know that there exists $a_1 > 0$ such that the map $\Psi_a$ is injective for all $a \in (0, a_1]$. We thus fix $a \in (0, a_1)$ and denote by $\Sigma_a$ the strip of width $2a$ enclosing $\Gamma$.

\[ \Sigma_a \equiv \Psi_a([0, L) \times (-a, a)). \]

Then the set $\mathbb{R}^2/\Sigma_a$ consists of two connected components which we denote by $\Lambda_a^{in}$ and $\Lambda_a^{out}$, where the interior one, $\Lambda_a^{in}$, is compact. We define a pair of quadratic forms,

\[ q_{c_0,B,a,\beta}^\pm(f; f) = |(-i \partial_x - \frac{c_0 y}{x^2 + y^2} + B y) f|^2_{L^2(\Sigma_a)} \]

\[ + |(-i \partial_y - \frac{c_0 x}{x^2 + y^2} - B x) f|^2_{L^2(\Sigma_a)} - \beta \int_\Gamma |f(x)|^2 ds \]

which are given by the same expression but differ by their domains, the latter in $H_0^1(\Sigma_a)$ for $q_{c_0,a,\beta}^+$ and $H^1(\Sigma_a)$ for $q_{c_0,a,\beta}^-$. Furthermore, we introduce the quadratic forms

\[ e_{c_0,B,a}^\pm(f; f) = |(-i \partial_x - \frac{c_0 y}{x^2 + y^2} + B y) f|^2_{L^2(\Lambda_a)} \]

\[ + |(-i \partial_y - \frac{c_0 x}{x^2 + y^2} - B x) f|^2_{L^2(\Lambda_a)} \]
for $j = \text{out, in}$, with the domain $H_0^1(\Sigma_a^j)$ and $H^1(\Sigma_a^j)$ corresponding to the $\pm$ sign respectively. Let $L^\pm_{co,B,a,\beta}$, $E^{\text{out,\pm}}_{co,B,a}$, and $E^{\text{in,\pm}}_{co,B,a}$ be the self-adjoint operators associated with the forms $q^\pm_{co,B,a,\beta}$, $e^{\text{out,\pm}}_{co,B,a}$, and $e^{\text{in,\pm}}_{co,B,a}$, respectively.

As in $[\text{3}]$ we are going to use the Dirichlet-Neumann bracketing with additional boundary conditions at the boundary of $\Sigma_a$. One can easily see this by comparing the form domains of the involved operators, cf. $[\text{4}]$ or $(\text{[6], thm XIII.2})$. We get

$$E^{\text{in,\pm}}_{co,B,a} \oplus L^{-}_{co,B,a,\beta} \oplus E^{\text{out,\pm}}_{co,B,a} \leq H_{co,B,a} \leq E^{\text{in,\pm}}_{co,B,a} \oplus L^{+}_{co,B,a,\beta} \oplus E^{\text{out,\pm}}_{co,B,a}$$

(2.7)

with the decomposed estimating operators in $L^2(\mathbb{R}^2) = L^2(\Sigma^a_{in}) \oplus L^2(\Sigma_a) \oplus L^2(\Sigma^a_{out})$. In order to assess the negative eigenvalues of $H_{co,B,a,\beta}$, it suffices to consider those of $L^{+}_{co,B,a,\beta}$ and $L^{-}_{co,B,a,\beta}$, because the other operators involved in (2.7) are positive. Since the loop is smooth, we can pass inside $\Sigma_a$ to the natural curvilinear coordinates. We state

$$(U_a f)(s,u) = (1 + u\gamma(s))^{1/2} f(\Psi_a(s,u)) \quad \text{for } f \in L^2(\Sigma_a)$$

which defines the unitary operator $U_a$ from $L^2(\Sigma_a)$ to $L^2([0,L] \times (-a,a))$. To express the estimating operators in the new variables, we introduce

$$Q^+_a = \{ \psi \in H^1((0,L) \times (-a,a)); \psi(L,.) = \psi(0,.) \text{on} (-a,a); \quad \psi(.,a) = \psi(.,-a) \text{on} (0,L) \}$$

$$Q^-_a = \{ \psi \in H^1((0,L) \times (-a,a)); \quad \psi(L,.) = \psi(0,.) \text{ on } (-a,a) \}$$

and define the quadratic forms

$$z^\pm_{co,B,a,\beta}[g] = \int_0^L \int_{-a}^{a} (1 + u\gamma(s))^{-2} |\partial_s g|^2 du ds + \int_0^L \int_{-a}^{a} |\partial_u g|^2 du ds$$

$$+ \int_0^L \int_{-a}^{a} V(s,u) |g|^2 du ds - \beta \int_0^L |g(s,0)|^2 ds$$

$$- \frac{b_+}{2} \int_0^L \frac{\gamma(s)}{1 + a\gamma(s)} |g(s,a)|^2 ds + \frac{b_-}{2} \int_0^L \frac{\gamma(s)}{1 - a\gamma(s)} |g(s,-a)|^2 ds$$

$$+ \int_0^L \int_{-a}^{a} \theta(s,u)^{-1} \left( c_0 \theta(s,u) + \frac{1}{2} B \right)^2 |g|^2 du ds$$

$$+ \text{Im} \int_0^L \int_{-a}^{a} \left( 2c_0 \theta(s,u) + B \right) (\Gamma_2 + u\Gamma'_1) \left( (1 + u\gamma)^{-1} \cos H \bar{\gamma} \partial_s g - \sin H \bar{\gamma} \partial_u g \right) du ds$$

$$- \text{Im} \int_0^L \int_{-a}^{a} \left( 2c_0 \theta(s,u) + B \right) (\Gamma_1 - u\Gamma'_2) \left( (1 + u\gamma)^{-1} \sin H \bar{\gamma} \partial_s g + \cos H \bar{\gamma} \partial_u g \right) du ds$$

(2.8)

on $Q^\pm_a$ respectively, where

$$V(s,u) = 1/2(1 + u\gamma(s))^{-3} u\gamma(s)^n - 5/4(1 + u\gamma(s))^{-4} u^2 \gamma(s)^2 - 1/4(1 + u\gamma(s))^{-2} \gamma(s)^2$$

$$\theta(s,u) = \left( \Gamma_1^2(s) + \Gamma_2^2(s) + u^2 - 2u(\Gamma_1(s)\Gamma_2(s) - \Gamma_2(s)\Gamma_1(s)) \right)^{-1}$$

on $Q^\pm_a$ respectively, where

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$b_+ = 0$ and $b_- = 1$. (2.8) can be written as

$$b_{c_0,B,a,\beta}^\pm[g] = \int_0^L \int_{-a}^a (1 + u\gamma(s))^{-2} |\partial_s g|^2 du ds + \int_0^L \int_{-a}^a |\partial_u g|^2$$

$$+ \int_0^L \int_{-a}^a V(s,u)|g|^2 du ds - \beta \int_0^L |g(s,0)|^2 ds$$

$$- \frac{b_+}{2} \int_0^L \frac{\gamma(s)}{1 + a\gamma(s)} |g(s,a)|^2 ds + \frac{b_-}{2} \int_0^L \frac{\gamma(s)}{1 - a\gamma(s)} |g(s,-a)|^2 ds$$

$$+ \int_0^L \int_{-a}^a \alpha_1(s,u)|g|^2 du ds$$

$$+ \text{Im} \int_0^L \int_{-a}^a \alpha_2(s,u) \left((1 + u\gamma)^{-1} \cos H\bar{\partial}_s g - \sin H\bar{\partial}_u g\right) du ds$$

$$- \text{Im} \int_0^L \int_{-a}^a \alpha_3(s,u) \left((1 + u\gamma)^{-1} \sin H\bar{\partial}_s g + \cos H\bar{\partial}_u g\right) du ds$$

$$= \int_0^L \int_{-a}^a (1 + u\gamma(s))^{-2} |\partial_s g|^2 du ds + \int_0^L \int_{-a}^a |\partial_u g|^2$$

$$+ \int_0^L \int_{-a}^a V(s,u)|g|^2 du ds - \beta \int_0^L |g(s,0)|^2 ds$$

$$- \frac{b_+}{2} \int_0^L \frac{\gamma(s)}{1 + a\gamma(s)} |g(s,a)|^2 ds + \frac{b_-}{2} \int_0^L \frac{\gamma(s)}{1 - a\gamma(s)} |g(s,-a)|^2 ds$$

$$+ \int_0^L \int_{-a}^a \alpha_1(s,u)|g|^2 du ds$$

$$+ \text{Im} \int_0^L \int_{-a}^a \left(\alpha_2(s,u) \cos H - \alpha_3(s,u) \sin H\right)(1 + u\gamma)^{-1}(\bar{\partial}_s g) du ds$$

$$- \text{Im} \int_0^L \int_{-a}^a \left(\alpha_3(s,u) \cos H - \alpha_2(s,u) \sin H\right)(1 + u\gamma)^{-1}(\bar{\partial}_u g) du ds$$

where

$$\alpha_1(s,u) = \theta(s,u)^{-1} \left(c_0 \theta(s,u) + \frac{1}{2} B\right),$$

$$\alpha_2(s,u) = \left(2c_0 \theta(s,u) + B\right)\left(\Gamma_2 + u \Gamma_1\right)$$

$$\alpha_3(s,u) = \left(2c_0 \theta(s,u) + B\right)\left(\Gamma_1 - u \Gamma_2\right)$$

Let $D_{c_0,B,a,\beta}^\pm$ be the self-adjoint operators associated with the forms $b_{c_0,B,a,\beta}^\pm$, respectively. By analogy with (3), we get the following result.

**Lemma 2.1** $U_a D_{c_0,B,a,\beta}^\pm U_a = L_{c_0,B,a,\beta}^\pm$.

In order to eliminate the coefficients of $\bar{\partial}_s g$ and $\bar{\partial}_u g$ in (2.8) modulo small errors, we employ the following unitary operator
\[
(M_{c_0,B}h)(s, u) = \exp[iK(s, u)]h(s, u). \tag{2.9}
\]

Replacing \(M_{c_0,B}h\) in (2.8), it becomes:

\[
v_{c_0,B,\alpha,\beta}[g] = \int_0^L \int_{-a}^a (1 + u\gamma(s))^{-2}|\partial_s g|^2duds + \int_0^L \int_{-a}^a |\partial_u g|^2
duds + \int_0^L \int_{-a}^a V(s, u)|g|^2dsdu - \beta \int_0^L |g(s, 0)|^2ds
- \frac{b_\pm}{2} \int_0^L \frac{\gamma(s)}{1 + a\gamma(s)}|g(s, a)|^2ds + \frac{b_\pm}{2} \int_0^L \frac{\gamma(s)}{1 - a\gamma(s)}|g(s, -a)|^2ds
+ \int_0^L \int_{-a}^a (\alpha_1(s, u) + |K_s|^2(1 + u\gamma(s))^{-2} + |K_u|^2 + K_u\Omega_1(s, u) - K_u\Omega_2(s, u))|g|^2duds
+ \text{Im} \int_0^L \int_{-a}^a (\Omega_1(s, u) + 2K_s(1 + u\gamma(s))^{-2})(\overline{g}\partial_s g)duds
- \text{Im} \int_0^L \int_{-a}^a (\Omega_2(s, u) - 2K_u)(\overline{g}\partial_u g)duds \tag{2.10}
\]

where

\[
\Omega_1(s, u) = \left(\alpha_2(s, u) \cos H - \alpha_3(s, u) \sin H\right)(1 + u\gamma)^{-1}, \tag{2.11}
\]

\[
\Omega_2(s, u) = \left(\alpha_3(s, u) \cos H - \alpha_2(s, u) \sin H\right)(1 + u\gamma)^{-1}. \tag{2.12}
\]

\[
K_s = \frac{\partial_s K(s, u)}{\partial s}, \quad K_u = \frac{\partial_u K(s, u)}{\partial u}, \quad g_s = \frac{\partial_s g(s, u)}{\partial s}, \quad g_u = \frac{\partial_u g(s, u)}{\partial u} \tag{2.13}
\]

To eliminate the coefficients of \(\overline{g}\partial_u g\) in \(c_{c_0,B,\alpha,\beta}[g]\), we have the following differential equation:

\[
\frac{\partial K(s, u)}{\partial u} = \frac{1}{2}\Omega_2(s, u) \tag{2.14}
\]

and then, we have

\[
K(s, u) = \frac{1}{2} \int_0^u \Omega_2(s, v)dv. \tag{2.15}
\]

This form of \(K\), reduces (2.10) to:
\[ \tilde{b}_{c_0,B,a,\beta}^\pm [g] = \int_0^L \int_{-a}^a (1 + u \gamma(s))^{-2} |\partial_s g|^2 duds + \int_0^L \int_{-a}^a |\partial_u g|^2 \\
+ \int_0^L \int_{-a}^a V(s,u)|g|^2 dsdu - \beta \int_0^L |g(s,0)|^2 ds \\
- \frac{b_+}{2} \int_0^L \frac{\gamma(s)}{1 + a\gamma(s)} |g(s,a)|^2 ds + \frac{b_+}{2} \int_0^L \frac{\gamma(s)}{1 - a\gamma(s)} |g(s,-a)|^2 ds \\
+ \int_0^L \int_{-a}^a \left( \alpha_1(s,u) + |K_s|^2(1 + u \gamma(s))^{-2} + |K_u|^2 + K_s \Omega_1(s,u) - K_u \Omega_2(s,u) \right) |g|^2 duds \\
+ \text{Im} \int_0^L \int_{-a}^a \left( \Omega_1(s,u) + 2K_s(1 + u \gamma(s))^{-2} \right) (\overline{g} \partial_s g) duds \] (2.16)

for \( g \in Q_a^\pm \), respectively.

Let \( \tilde{D}_{c_0,B,a,\beta} \) be the self-adjoint operators associated with the forms \( \tilde{b}_{c_0,B,a,\beta}^\pm \), respectively. We have the following result

**Lemma 2.2** \( M_{c_0,B}^* D_{c_0,B,a,\beta}^\pm M_{c_0,B} = \tilde{D}_{c_0,B,a,\beta}^\pm \).

In the estimation of the \( \tilde{D}_{c_0,B,a,\beta}^\pm \), let us use the same notation as in [4]:

\[ \gamma_+ = \max_{[0,L]} |\gamma(\cdot)| \]

\[ N_{c_0,B}(a) = \max_{(s,u) \in [0,L] \times [-a,a]} \left| \left( \Omega_1(s,u) + 2K_s(1 + u \gamma(s))^{-2} \right) \right| \]

and

\[ M_{c_0,B}(a) := \max_{(s,u) \in [0,L] \times [-a,a]} |W_{c_0,B}(s,u) + \frac{1}{4} \gamma(s)^2|; \]

where

\[ W_{c_0,B}(s,u) = V(s,u) + \alpha_1(s,u) + |K_s|^2(1 + u \gamma(s))^{-2} + |K_u|^2 + K_s \Omega_1(s,u) - K_u \Omega_2(s,u). \] (2.17)

Since \((c_0, B) \in I\), then there exists \( T \) such that \( N_{c_0,B}(a) + M_{c_0,B}(a) \leq Ta \) for \( 0 < a < \frac{1}{2\gamma_+} \) and \((c_0, B) \in I\), where \( T \) is independent of \( a, c_0 \) and \( B \). For fixed \( 0 < a < \frac{1}{2\gamma_+} \), as in [4] we define

\[ \tilde{b}_{c_0,B,a,\beta}^\pm [g] = \int_0^L \int_{-a}^a \left( [(1 \pm u \gamma_+)^{-2} \pm \frac{1}{2} N_{c_0,B}(a)] |\partial_s g|^2 + |\partial_u g|^2 \right) \\
+ \left[ -\frac{1}{4} \gamma(s)^2 \pm \frac{1}{2} N_{c_0,B}(a) \pm M_{c_0,B}(a) \right] |g|^2 duds \\
- \beta \int_0^L |g(s,0)|^2 ds - \gamma_+ b_\pm \int_0^L \left( |g(s,a)|^2 + |g(s,-a)|^2 \right) ds \] (2.18)

for \( g \in Q_a^\pm \), respectively. Since \( \left| \text{Im}(\overline{g} \partial_s g) \right| \leq \frac{1}{2} \left( |g|^2 + |\partial_s g|^2 \right) \), we obtain
Proposition 2.1 Let \( \mu_j \) be the \( j \)-th eigenvalue of the following operator, define on \( L^2([0, L]) \), by

\[
U_{a,b}^\pm = - \left[ (1 + u\gamma_+)^{-2} \pm \frac{1}{2} N_{c_0,B}(a) \right] \frac{d^2}{ds^2} - \frac{1}{4} \gamma(s)^2 \pm \frac{1}{2} N_{c_0,B}(a) \pm M_{c_0,B}(a) \tag{2.21}
\]

in \( L^2((0, L)) \) with the domain \( P_{c_0} \) specified in the previous section. Then we have

\[
\hat{H}_{c_0,B,a,b}^\pm = U_{c_0,B,a}^\pm \otimes 1 + 1 \otimes T_{a,b}^\pm. \tag{2.22}
\]

Let \( \mu_j^\pm(c_0, B, a) \) be the \( j \)-th eigenvalue of \( U_{c_0,B,a}^\pm \) counted with multiplicity. We shall prove the following estimate as in \( [4] \).

**Proposition 2.1** Let \( j \in \mathbb{N} \). Then there exists \( C(j) > 0 \) such that

\[
|\mu_j^+(c_0, B, a) - \mu_j(c_0, B)| + |\mu_j^-(c_0, B, a) - \mu_j(c_0, B)| \leq C(j)a
\]

holds for \( (c_0, B) \in I \) and \( 0 < a < \frac{1}{2\gamma_+} \), where \( C(j) \) is independent of \( c_0, B \) and \( a \).

**Proof:** Since

\[
U_{c_0,B,a}^+ = \left[ (1 - a\gamma_+)^{-2} + \frac{1}{2} N_{c_0,B}(a) \right] S_{c_0,B}
\]

\[
= \frac{1}{4} \left[ \frac{a\gamma_+(2 - a\gamma_+)}{(1 - a\gamma_+)^2} + \frac{1}{2} N_{c_0,B}(a) \right] \gamma(s)^2 + \frac{1}{2} N_{c_0,B}(a) + M_{c_0,B}(a),
\]

\( N_{c_0,B}(a) + M_{c_0,B}(a) \leq Ta \) for \( 0 < a < \frac{1}{2\gamma_+} \) and \( (c_0, B) \in I \), we infer that there is a constant \( C_1 > 0 \) such that

\[
\|U_{c_0,B,a}^+ - \left[ (1 - a\gamma_+)^{-2} + \frac{1}{2} N_{c_0,B}(a) \right] S_{c_0,B}\| \leq C_1 a
\]
for $0 < a < \frac{1}{2^{\gamma+}}$ and $(c_0, B) \in I$. This together with the min-max principle implies that
\[
|\mu_j^+(c_0, B, a) - \left((1-a\gamma^+)^{-2} + \frac{1}{2}N_{c_0,B}(a)\right)\mu_j(c_0, B)| \leq C_1 a
\]
for $0 < a < \frac{1}{2^{\gamma+}}$ and $(c_0, B) \in I$. Since $\mu_j(\cdot, \cdot)$ is continuous, we claim that there exists a constant $C_2 > 0$ such that
\[
|\mu_j^+(c_0, B, a) - \mu_j(c_0, B)| \leq C_2 a
\]
for $0 < a < \frac{1}{2^{\gamma+}}$ and $(c_0, B) \in I$. In a similar way, we infer the existence of a constant $C_3 > 0$ such that
\[
|\mu_j^-(c_0, B, a) - \mu_j(c_0, B)| \leq C_3 a
\]
for $0 < a < \frac{1}{2^{\gamma+}}$ and $(c_0, B) \in I$.

Let us recall the following result from [3].

**Proposition 2.2** (a) Suppose that $\beta a > \frac{8}{3}$. Then $T^+_{a,\beta}$ has only one negative eigenvalue, which we denote by $\zeta_{a,\beta}^+$. It satisfies the inequality
\[
-\frac{1}{4}\beta^2 < \zeta_{a,\beta}^+ < -\frac{1}{4}\beta^2 + 2\beta^2 \exp\left(\frac{1}{2}\beta\right).
\]
(b) Let $\beta > 8$ and $\beta > \frac{8}{3}\gamma^+$. Then $T^-_{a,\beta}$ has a unique negative eigenvalue $\zeta_{a,\beta}^-$, and moreover, we have
\[
-\frac{1}{4}\beta^2 - \frac{2005}{16}\beta^2 \exp\left(\frac{1}{2}\beta\right) < \zeta_{a,\beta}^- < -\frac{1}{4}\beta^2.
\]

**Proof of theorem 2.1**

We take $a(\beta) = 6\beta^{-1} \ln \beta$. Let $\xi_{\beta,j}^\pm$ be the $j$-th eigenvalue of $T^\pm_{a(\beta),\beta}$, by Proposition 2.2 we have
\[
\xi_{\beta,1}^\pm = \zeta_{a(\beta),\beta}^\pm, \quad \xi_{\beta,2}^\pm \geq 0.
\]
From the decompositions (2.22) we infer that $\{\xi_{\beta,j}^\pm + \mu_k^\pm(c_0, B, a(\beta))\}_{j,k \in \mathbb{N}}$ properly ordered, is the sequence of the eigenvalues of $\tilde{H}_{c_0,B,a(\beta),\beta}^\pm$ counted with multiplicity. Propositions 2.1 gives
\[
\xi_{\beta,j}^\pm + \mu_k(c_0, B, a(\beta)) \geq \mu_1^+(c_0, B, a(\beta)) = \mu_1(c_0, B) + O(\beta^{-1} \ln \beta) \tag{2.23}
\]
for $(c_0, B) \in I$, $j \geq 2$, and $k \geq 1$, where the error term is uniform with respect to $(c_0, B) \in I$. For a fixed $j \in \mathbb{N}$, we take
\[
\tau_{c_0,B,\beta,j}^\pm = \zeta_{a(\beta),\beta}^\pm + \mu_j^\pm(c_0, B, a(\beta)).
\]
Combining Propositions 2.1 and 2.2 we get
\[
\tau_{c_0,B,\beta,j}^\pm = -\frac{1}{4}\beta^2 + \mu_j(c_0, B) + O(\beta^{-1} \ln \beta) \quad \text{as} \quad \beta \to \infty, \tag{2.24}
\]
where the error term is uniform with respect to \((c_0, B) \in I\). Let us fix \(n \in \mathbb{N}\). Combining (2.23) with (2.24) we infer that there exists \(\beta(n, I) > 0\) such that the inequalities

\[
\tau_{c_0,B,\beta,n}^+ < 0, \quad \tau_{c_0,B,\beta,n}^- < \xi_{\beta,j}^+ + \mu_k(c_0, B, a(\beta)), \quad \tau_{c_0,B,\beta,n}^- < \xi_{\beta,j}^- + \mu_k(c_0, B, a(\beta))
\]

hold for \((c_0, B) \in I, \beta \geq \beta(n, I), j \geq 2, \) and \(k \geq 1\). Hence the \(j\)-th eigenvalue of \(\hat{H}_{c_0,B,a(\beta),\beta}\) counted with multiplicity is \(\tau_{c_0,B,\beta,j}^+\) for \((c_0, B) \in I, j \leq n, \) and \(\beta \geq \beta(n, I)\). Let \((c_0, B) \in I\) and \(\beta \geq \beta(n, I)\). We denote by \(\kappa_j(c_0, B, \beta)\) the \(j\)-th eigenvalue of \(L_{c_0,B,a(\beta),\beta}\). Combining our basic estimate and the result of [4] with Lemmas 2.1 and 2.2 relations 2.19 and 2.20 and the min-max principle, we arrive at the inequalities

\[
\tau_{c_0,B,\beta,j}^- \leq \kappa_j^-(c_0, B, \beta) \quad \text{and} \quad \kappa_j^+(c_0, B, \beta) \leq \tau_{c_0,B,\beta,j}^+ \quad \text{for} \quad 1 \leq j \leq n,
\]

so we have \(\kappa_n^+(c_0, B, \beta) < 0 < \inf \sigma_{\text{ess}}(H_{c_0,B,\beta})\). Hence the min-max principle and and the result of [6] imply that \(H_{c_0,B,\beta}\) has at least \(n\) eigenvalues in \((-\infty, \kappa_n^+(c_0, B, \beta)]\). Given \(1 \leq j \leq n\), we denote by \(\lambda_j(c_0, B, \beta)\) the \(j\)-th eigenvalue of \(H_{c_0,B,\beta}\). It satisfies

\[
\kappa_j^-(c_0, B, \beta) \leq \lambda_j(c_0, B, \beta) \leq \kappa_j^+(c_0, B, \beta) \quad \text{for} \quad 1 \leq j \leq n;
\]

this together with (2.24) and (2.25) implies that

\[
\lambda_j(c_0, B, \beta) = -\frac{1}{4} \beta^2 + \mu_j(c_0, B) + O(\beta^{-1} \ln \beta) \quad \text{as} \quad \beta \to \infty \quad \text{for} \quad 1 \leq j \leq n,
\]

where the error term is uniform with respect to \((c_0, B) \in I\). This completes the proof.

**Proof of corollary 2.1** The theorem 2.1 with [6] (theorem XIII.89) yields the claim.

### 3 Remarks

Here, if we take \(c_0 = 0\) we recovered the results of [3]. If we take \(B = 0\), we recovered the results of [5].

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