Weyl asymptotics for perturbed functional difference operators

Laptev, Ari; Schimmer, Lukas; Takhtajan, Leon A.

Published in:
Journal of Mathematical Physics

DOI:
10.1063/1.5093401

Publication date:
2019

Document version
Publisher's PDF, also known as Version of record

Document license:
Other

Citation for published version (APA):
Weyl asymptotics for perturbed functional difference operators

Cite as: J. Math. Phys. 60, 103505 (2019); https://doi.org/10.1063/1.5093401
Submitted: 20 February 2019 . Accepted: 24 September 2019 . Published Online: 11 October 2019

Ari Laptev, Lukas Schimmer, and Leon A. Takhtajan

COLLECTIONS

Paper published as part of the special topic on XIXth International Congress on Mathematical Physics
Note: This paper is part of the Special Collection: XIXth International Congress on Mathematical Physics.

ARTICLES YOU MAY BE INTERESTED IN

Symmetries of the space of solutions to special double confluent Heun equations of integer order
Journal of Mathematical Physics 60, 103501 (2019); https://doi.org/10.1063/1.5030955

A novel examination of the similarity between a perturbed hydrogen atom and an anharmonic oscillator
Journal of Mathematical Physics 60, 102102 (2019); https://doi.org/10.1063/1.5086981

Time-dependent polynomials with one multiple root and new solvable dynamical systems
Journal of Mathematical Physics 60, 103503 (2019); https://doi.org/10.1063/1.5050628
Weyl asymptotics for perturbed functional difference operators

Cite as: J. Math. Phys. 60, 103505 (2019); doi: 10.1063/1.5093401
Submitted: 20 February 2019 • Accepted: 24 September 2019 •
Published Online: 11 October 2019

Ari Laptev, Lukas Schimmer, and Leon A. Takhtajan

AFFILIATIONS

1 Department of Mathematics, Imperial College London, SW7 2AZ London, United Kingdom and Institut Mittag-Leffler and Saint Petersburg University, Saint Petersburg, Russia
2 QMATH, Department of Mathematical Sciences, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen Ø, Denmark
3 Department of Mathematics, Stony Brook University, Stony Brook, New York 11794-3651, USA and Euler Mathematical Institute, Saint Petersburg, Russia

Note: This paper is part of the Special Collection: XIXth International Congress on Mathematical Physics.

Email: a.laptev@imperial.ac.uk
Email: schimmer@math.ku.dk
Email: leontak@math.stonybrook.edu

ABSTRACT

We consider the difference operator $H_W = U + U^{-1} + W$, where $U$ is the self-adjoint Weyl operator $U = e^{-bP}$, $b > 0$, and the potential $W$ is of the form $W(x) = x^{2N} + r(x)$ with $N \in \mathbb{N}$ and $|r(x)| \leq C(1 + |x|^{2N-\varepsilon})$ for some $0 < \varepsilon \leq 2N - 1$. This class of potentials $W$ includes polynomials of even degree with leading coefficient 1, which have recently been considered in Grassi and Mariño [SIGMA Symmetry Integrability Geom. Methods Appl. 15, 025 (2019)]. In this paper, we show that such operators have discrete spectrum and obtain Weyl-type asymptotics for the Riesz means and for the number of eigenvalues. This is an extension of the result previously obtained in Laptev et al. [Geom. Funct. Anal. 26, 288–305 (2016)] for $W = V + \zeta V^{-1}$, where $V = e^{2ab\xi}$, $\zeta > 0$.

Published under license by AIP Publishing. https://doi.org/10.1063/1.5093401

I. INTRODUCTION

The mirror manifolds of toric Calabi–Yau manifolds can be described by algebraic curves and recently it was observed that quantization of these curves leads to functional-difference operators. For local del Pezzo Calabi–Yau threefolds, the simplest example yields the operator $H_{\text{CY}} = U + U^{-1} + V + \zeta V^{-1}$ on $L^2(\mathbb{R})$. Here, $U$ and $V$ denote the self-adjoint Weyl operators $U = e^{-bP}$ and $V = e^{2ab\xi}$ for $b > 0$, where $(P\psi)(x) = i\psi'(x)$ and $(Q\psi)(x) = x\psi(x)$ are the quantum mechanical momentum and position operators on $L^2(\mathbb{R})$.

In a recent paper, the authors proved that for $\zeta > 0$, the operator $H_{\text{CY}}$ has a self-adjoint extension with purely discrete spectrum consisting of finite multiplicity eigenvalues tending to infinity. In addition, Weyl-type asymptotics for the Riesz means and for the number of eigenvalues were established. These results prove that $H_{\text{CY}}^{1/2}$ is trace-class, which confirms part of a conjecture in Ref. 2. In this short note, we consider the difference operator

$H_W = U + U^{-1} + W = H_0 + W,$

where $W \in C(\mathbb{R})$ is a continuous, real-valued potential satisfying $\lim_{|x| \to \infty} W(x) = \infty$ that is of the form $W(x) = x^{2N} + r(x)$ with $N \in \mathbb{N}$ and $|r(x)| \leq C(1 + |x|^{2N-\varepsilon})$ for some $0 < \varepsilon \leq 2N - 1$. This class of potentials includes polynomials of even degree with leading coefficient 1, which have recently been considered in Ref. 3. We will prove that such an operator admits a self-adjoint extension with discrete eigenvalues $\lambda_j$ of finite multiplicity converging to infinity. Subsequently we will prove Weyl-type asymptotics for the Riesz mean $\sum_{\lambda_j} (\lambda - \lambda_j)$, and for the number of eigenvalues below a given value $\lambda$ as $\lambda \to \infty$ (note that the Riesz means for the negative spectrum of Schrödinger operators with decaying...
pots are associated with Lieb–Thirring inequalities (3). These results prove that, if $H_W$ is invertible, the inverse $H_W^{-1}$ is trace-class, as claimed in Ref. 3. Our proof method also applies to the previously considered potential $V + V^{-1}$.

II. MAIN RESULTS

Since $W \in C(\mathbb{R})$ with $\lim_{|x| \to \infty} W(x) = \infty$, we can conclude that $W$ is bounded from below. As a consequence, the symmetric operator $H = H_0 + W$ is bounded from below on the common domain of $H_0$ and $W$. We can thus consider its self-adjoint Friedrichs extension, which we continue to denote by $H$. The following proposition was proved in Ref. 8.

Proposition 1 (Ref. 8, Proposition 2.1). Let $W(x)$ be a continuous, real-valued, bounded below function such that $\lim_{|x| \to \infty} W(x) = +\infty$. Then, the operator $H_W = H_0 + W$ has purely discrete spectrum consisting of finite multiplicity eigenvalues tending to $+\infty$.

In Ref. 8, we considered the potential $W(x) = 2 \cosh(2\pi bx)$ and proved the following result.

**Theorem 2** (Ref. 8, Theorem 2.2). For the eigenvalues $\lambda_j$ of $H_0 + 2 \cosh(2\pi bx)$, it holds that

$$\lim_{\lambda \to \infty} \int_{\mathbb{R}} (\lambda - 2 \cosh(2\pi bx) - 2 \cosh(2\pi bx)) \, dk \, dx = \lim_{\lambda \to \infty} \frac{1}{(2\pi)^2} \log^2 \lambda = 1$$

with a lower order term of the form $O(\lambda \log \lambda)$.

Here, $a_+ = (a + |a|)/2$ denotes the positive part of a real variable. We also obtained the asymptotics for the number of eigenvalues smaller than $\lambda$.

**Corollary 3** (Ref. 8, Corollary 2.3). For the number of eigenvalues $N(\lambda) = \# \{ j \geq 1 : \lambda_j < \lambda \}$ of $H_0 + 2 \cosh(2\pi bx)$ smaller than $\lambda$, it holds that

$$\lim_{\lambda \to \infty} \int_{|x| \geq \epsilon} N(\lambda) \, dx = \lim_{\lambda \to \infty} \frac{1}{(2\pi)^2} \log^2 \lambda = 1.$$ 

In this short note, we will prove the following analogous result for potentials growing polynomially.

**Theorem 4** Let $N \in \mathbb{N}$ and let $r \in C(\mathbb{R})$ be a function such that $|r(x)| \leq C(1 + |x|^{2N} - \epsilon)$ for some $C > 0, 2N - 1 \geq \epsilon > 0$ and all $x \in \mathbb{R}$. For the eigenvalues $\lambda_j$ of $H_0 + x^{2N} + r(x)$, it holds that

$$\lim_{\lambda \to \infty} \int_{\mathbb{R}} (\lambda - 2 \cosh(2\pi bx) - x^{2N} - r(x)) \, dk \, dx = \lim_{\lambda \to \infty} \frac{1}{2\pi} \frac{\sum_{j \geq 1} (\lambda - \lambda_j)_+}{\sum_{j \geq 1} (\lambda - \lambda_j)_+} \log \lambda = 1$$

with a lower order term of the form $O(\lambda^{\frac{1}{2N+1}})$.

**Corollary 5**. Let $N \in \mathbb{N}$ and let $r \in C(\mathbb{R})$ be a function such that $|r(x)| \leq C(1 + |x|^{2N} - \epsilon)$ for some $C > 0, 2N - 1 \geq \epsilon > 0$ and all $x \in \mathbb{R}$. For the number of eigenvalues $N(\lambda) = \# \{ j \geq 1 : \lambda_j < \lambda \}$ of $H_0 + x^{2N} + r(x)$ smaller than $\lambda$, it holds that

$$\lim_{\lambda \to \infty} \int_{|x| \geq \epsilon} N(\lambda) \, dx = \lim_{\lambda \to \infty} \frac{1}{2\pi} \frac{N(\lambda)}{\lambda} \log \lambda = 1.$$ 

**Remark 6**. Let $H_0 + x^{2N} + r_0(x)$ satisfy the assumptions of Theorem 4. If the operator is invertible, as is, for example, the case if $x^{2N} + r_0(x) \geq \epsilon > -2$, then we can repeat the argument of Ref. 8 to prove that $(H_0 + x^{2N} + r_0(x)^{-1}$ is trace-class. Assuming for simplicity that $\lambda_1 > 0$, this follows from

$$\sum_{j \geq 1} \frac{1}{|\lambda_j|} = \int_{\lambda_1}^{\infty} \frac{1}{\lambda} \, dN(\lambda) = \frac{N(\lambda)}{\lambda} \bigg|_{\lambda_1}^{\infty} + \int_{\lambda_1}^{\infty} \frac{N(\lambda)}{\lambda^2} \, d\lambda < \infty.$$
Remark 7. The total symbol of the operator $H_0 + W$ is given by

$$\sigma(x,k) = 2 \cosh(2\pi b k) + W(x).$$

Theorems 2 and 4 as well as Corollaries 3 and 5 are Weyl-type results that link the asymptotic behavior of quantum mechanical expressions to classical phase space integrals.

In Sec. III, we will give proofs of Theorems 2 and 4. It follows our arguments in Ref. 8, where the special case of $W(x) = 2\cosh(2\pi b x)$ was considered. In Sec. IV we will prove Corollaries 3 and 5. Before we proceed with the proofs, we compute the explicit asymptotics of the phase space integrals. This will prove equality between the limits in the results above.

A. Leading order terms for hyperbolic cosine potential

In Ref. 8, we computed that for any $C, D > 0$,

$$\iint_{R^2} (\lambda - 2D \cosh(2\pi b k) - 2C \cosh(2\pi b x)) \, dk\, dx = \frac{\lambda \log^2 \lambda}{(\pi b)^2} + O(\lambda \log \lambda) \quad (1)$$

as $\lambda \to \infty$ and similarly

$$\iint_{|\lambda - 2D \cosh(2\pi b k) - 2C \cosh(2\pi b x)| \geq 0} \, dk\, dx = \frac{\log^2 \lambda}{(\pi b)^2} + o(\log^2 \lambda) \quad (2)$$

as $\lambda \to \infty$.

B. Leading order terms for polynomial potential

Let $N \in \mathbb{N}$. By the min-max principle, it is sufficient to consider $r(x) = C(1 + |x|^{2N-\epsilon})$ with $C \in \mathbb{R}$ and prove that the asymptotic behavior of the phase space integrals is independent of $C$ as $\lambda \to \infty$. For later reference, we will also include an additional multiplication factor $D > 0$ in front of the term $2 \cosh(2\pi b k)$ and prove that the asymptotic behaviour does not depend on $D$.

Using the symmetry of the integrand as well as $2 \cosh(2\pi b k) \geq e^{2\pi b k}$ for $k > 0$ together with the substitution $u = De^{2\pi b k}$, we can compute that

$$\iint_{R^2} (\lambda - 2D \cosh(2\pi b k) - x^{2N} - C(1 + |x|^{2N-\epsilon})) \, dk\, dx \leq 4 \int_0^{\infty} (\lambda - De^{2\pi b k} - x^{2N} - C(1 + x^{2N-\epsilon})) \, dk\, dx = \frac{2}{\pi b} \int_0^{\infty} \int_0^{\infty} (\lambda - u - x^{2N} - C(1 + x^{2N-\epsilon})) \, du\, dv.$$ 

Substituting $v_1 \lambda = u$ and $v_2 \lambda^{1/(2N)} = x$, we obtain

$$\iint_{R^2} (\lambda - 2D \cosh(2\pi b k) - x^{2N} - C(1 + |x|^{2N-\epsilon})) \, dk\, dx \leq \frac{2\lambda^{2N+\epsilon}}{\pi b} \int_{D/\lambda}^{\infty} \int_0^{\infty} \frac{(1 - v_1 - v_2^{2N} - C \lambda^{-1} - C v_2^{2N-\epsilon} \lambda^{-\frac{\epsilon}{2}})}{v_1} \, dv_2\, dv_1.$$ 

Note that the domain of integration can be restricted to $v_2 \geq 0$ and $1 - v_1 - v_2^{2N} - C \lambda^{-1} - C v_2^{2N-\epsilon} \lambda^{-\frac{\epsilon}{2}} \geq 0$. We now use that $(a - b)_+ \leq a_+ + |b|$ for any $a, b \in \mathbb{R}$ to split the integral into two parts

$$\iint_{R^2} (\lambda - 2D \cosh(2\pi b k) - x^{2N} - C(1 + |x|^{2N-\epsilon})) \, dk\, dx \leq \frac{2\lambda^{2N+\epsilon}}{\pi b} \left( \int_{D/\lambda}^{1} \int_0^{\infty} \frac{(1 - v_1 - v_2^{2N})}{v_1} \, dv_2\, dv_1 \right. \left. + |C| \int_{D/\lambda}^{\infty} \int_{v_1^{2N-\epsilon} \geq 0} \frac{\lambda^{-1} + v_2^{2N-\epsilon} \lambda^{-\frac{\epsilon}{2}}}{v_1} \, dv_2\, dv_1 \right).$$
The first integral yields the correct leading order term. To prove this, we first compute the inner integral explicitly

\[
\frac{2\lambda^{\frac{N+i}{b}}}{\pi b} \int_{D/\lambda}^{1} \int_{0}^{\infty} \frac{(1 - v_1 - v_2^2)}{v_1} \, dv_2 \, dv_1 = \frac{2}{\pi b} \frac{2N}{2N+1} \lambda^{\frac{N+i}{b}} \int_{D/\lambda}^{1} \frac{(1 - v_1)}{v_1} \, dv_1.
\]

Using partial integration, we then observe that

\[
\int_{D/\lambda}^{1} \frac{(1 - v_1)}{v_1} \, dv_1 = \log \left( \frac{1}{D} \right) \left( 1 - \frac{D}{\lambda} \right)^{\frac{N+i}{b}} + \frac{2N+1}{2N} \int_{D/\lambda}^{1} \frac{(1 - v_1)^{\frac{N}{b}}}{v_1} \log v_1 \, dv_1.
\]

It remains to note that

\[
\left| \int_{D/\lambda}^{1} (1 - v_1)^{\frac{N}{b}} \log v_1 \, dv_1 \right| = \int_{D/\lambda}^{1} (1 - v_1)^{\frac{N}{b}} \log \left( \frac{1}{v_1} \right) \, dv_1 \leq \left( 1 - \frac{D}{\lambda} \right)^{\frac{N}{b}} \left( 1 - \frac{D}{\lambda} - \frac{D}{\lambda} \log \left( \frac{1}{D} \right) \right)
\]

to establish the asymptotic behavior

\[
\frac{2\lambda^{\frac{N+i}{b}}}{\pi b} \int_{D/\lambda}^{1} \int_{0}^{\infty} \frac{(1 - v_1 - v_2^2)}{v_1} \, dv_2 \, dv_1 = \frac{2}{\pi b} \frac{2N}{2N+1} \lambda^{\frac{N+i}{b}} \log \lambda + O(\lambda^{\frac{N+i}{b}})
\]
as \(\lambda \to \infty\). For the second integral, we use that for sufficiently large \(\lambda\),

\[
1 - v_1 = v_2^{2N} - C\lambda^{-1} - Cv_2^{2N-\epsilon} \lambda^{-\frac{N}{b}} \leq 2 - v_1 = \frac{1}{2} v_2^{2N}
\]

and that

\[
\int_{D/\lambda}^{\infty} \int_{v_2 \geq 0} \frac{\lambda^{-1} + v_2^{2N-\epsilon} \lambda^{-\frac{N}{b}}}{v_1} \, dv_2 \, dv_1 \leq \lambda^{-\frac{N}{b}} \int_{D/\lambda}^{2} \int_{0}^{v_2^{2N}} \frac{5}{v_1} \, dv_2 \, dv_1
\]
\[
\leq 10\lambda^{-\frac{N}{b}} \log \lambda - \log D + \log 2
\]
since \(\lambda^{-\frac{N}{b}} + v_2^{2N-\epsilon} \leq 5\) on the domain of integration for sufficiently large \(\lambda\). Putting everything together and using that \(\lim_{\lambda \to \infty} (\frac{2N}{2N+1} \log \lambda) / \lambda^{\frac{N+i}{b}} = 0\) since \(\epsilon > 0\), we obtain that

\[
\iint_{\mathbb{R}^2} (\lambda - 2D \cosh(2\pi k) - x^{2N} - C(1 + |x|^{2N-\epsilon})), \, dk \, dx
\]
\[
\leq \frac{2}{\pi b} \frac{2N}{2N+1} \lambda^{\frac{N+i}{b}} \log \lambda + O(\lambda^{\frac{N+i}{b}})
\]
as \(\lambda \to \infty\). Similarly, we can use the fact that \(2 \cosh(2\pi k) \leq 2e^{2\pi k}\) for \(k > 0\) together with the substitution \(u = 2De^{2\pi k}\) to obtain the lower bound

\[
\iint_{\mathbb{R}^2} (\lambda - 2D \cosh(2\pi k) - x^{2N} - C(1 + |x|^{2N-\epsilon})), \, dk \, dx
\]
\[
\geq 4 \int_{0}^{\infty} \int_{0}^{\infty} (\lambda - 2De^{2\pi k} - x^{2N} - C(1 + x^{2N-\epsilon})), \, dk \, dx
\]
\[
= \frac{2}{\pi b} \int_{2D}^{\infty} \int_{0}^{\infty} (\lambda - u - x^{2N} - C(1 + x^{2N-\epsilon})), \, du \, dx
\]
and by similar arguments as above

\[
\iint_{\mathbb{R}^2} (\lambda - 2D \cosh(2\pi k) - x^{2N} - C(1 + |x|^{2N-\epsilon})), \, dk \, dx
\]
\[
\geq \frac{2}{\pi b} \frac{2N}{2N+1} \lambda^{\frac{N+i}{b}} \log \lambda + O(\lambda^{\frac{N+i}{b}})
\]
as \( \lambda \to \infty \). Together with the upper bound, we obtain that

\[
\int_{\mathbb{R}} (\lambda - 2 \cosh(2\pi b k) - x^{2N} - C(1 + |x|^{2N-2})) \, dk \, dx = \frac{2}{\pi b} \frac{2N}{2N + 1} \lambda^{\frac{2N}{2N + 1}} \log \lambda + O(\lambda^{\frac{2N}{2N + 1}}).
\]

Similarly, we can show that as \( \lambda \to \infty \),

\[
\int_{\mathbb{R}^2} \cosh(2\pi b k) - x^{2N} - C(1 + |x|^{2N-2}) \geq 0 \, dk \, dx = \frac{2}{\pi b} \lambda^{\frac{2N}{2N + 1}} \log \lambda + o(\lambda^{\frac{2N}{2N + 1}} \log \lambda).
\]

III. THE PROOF OF THEOREMS 2 AND 4

To establish upper and lower bounds on the sum of the eigenvalues, we will employ ideas from Ref. 6, with the Fourier transform replaced by the coherent state transform, which we will introduce below.

Let \( g_\beta \) be the Gaussian function \( g_\beta(x) = (\beta/\pi)^{1/4} e^{-\beta x^2} \) with some \( \beta > 0 \), fixed for the moment. Clearly \( g_\beta \) satisfies \( \|g_\beta\|^2 = 1 \) in \( L^2(\mathbb{R}) \). For \( \psi \in L^2(\mathbb{R}) \), the classical coherent state transform is given by

\[
\tilde{\psi}(k, y) = \int_{\mathbb{R}} e^{-2mk} g_\beta(x - y) \psi(x) \, dx = (\psi, c_{k,y}),
\]

where \( c_{k,y} = e^{-mk} g_\beta(x - y) \). Following the computations in Ref. 8, we can show that

\[
\int_{\mathbb{R}} d\beta \, 2 \cosh(2\pi b k) \tilde{\psi}(k, y)^2 \, dk = \int_{\mathbb{R}} (H_0 \psi)(x) \tilde{\psi}(x) \, dx,
\]

where \( d\beta = e^{-\beta^2/4} < 1 \). A standard computation furthermore shows that

\[
\int_{\mathbb{R}^2} W(y) \tilde{\psi}(k, y)^2 \, dy = \int_{\mathbb{R}^2} (W * g_\beta^2)(x) \tilde{\psi}(x)^2 \, dx.
\]

For convenience, we set \( W_\beta := W * g_\beta^2 \). Note that \( W_\beta \in C(\mathbb{R}) \) with \( \inf_{x \in \mathbb{R}} W_\beta(x) \geq \inf_{x \in \mathbb{R}} W(x) \) since \( g_\beta \) is non-negative and \( \|g_\beta\|_2 = 1 \). Furthermore, \( \lim_{|x| \to \infty} W_\beta(x) = \infty \) and thus the statements above on the self-adjoint extension and discreteness of the spectrum also hold for the operator \( H_0 + W_\beta \).

We now establish results for the special case of a hyperbolic cosine potential as well as monomial potentials. In Ref. 8, Sec. 2.1, we proved the following.

**Proposition 8.** Let \( b > 0 \). Then,

\[
(2 \cosh(2\pi bx) * g_\beta^2)(x) = \frac{1}{c_\beta} 2 \cosh(2\pi bx),
\]

where \( c_\beta = e^{-(\beta b^2)/\beta} \). Conversely,

\[
2 \cosh(2\pi bx) = (c_\beta 2 \cosh(2\pi bx) * g_\beta^2)(x).
\]

An analogous result holds for monomials.

**Proposition 9.** Let \( N \in \mathbb{N} \). Then,

\[
(x^{2N} * g_\beta^2)(x) = x^{2N} + p_N(x),
\]

where \( p_N(x) = \sum_{j=0}^{N-1} \frac{1}{b_j} a_N b_j x^{2j} \) is an even polynomial of order \( 2N - 2 \) with coefficients \( a_N \) independent of \( \beta \). Conversely,

\[
x^{2N} = ((x^{2N} + q_N) * g_\beta^2)(x),
\]

where \( q_N(x) = \sum_{j=0}^{N-1} \frac{1}{b_j} b_N b_j x^{2j} \) is an even polynomial of order \( 2N - 2 \) with coefficients \( b_N \) independent of \( \beta \).

Furthermore, for \( 0 < \epsilon \leq 2N - 1 \), it holds that

\[
(|x|^{2N-\epsilon} * g_\beta^2)(x) \leq c_{\epsilon,N}(1 + |x|^{2N-\epsilon})
\]
with some constant $c_{\epsilon,N} \geq 0$ depending on $\beta$ and conversely

$$|x|^{2N-\epsilon} \leq (|x|^{2N-\epsilon} * g^2_\epsilon)(x).$$

Proof. Writing

$$\int_{\mathbb{R}} (x - y)^{2N} g_\epsilon(y)^2 \, dy = \sum_{k=0}^{2N} \binom{2N}{k} x^k \int_{\mathbb{R}} y^{2N-k} g_\epsilon(y)^2 \, dy$$

and noting that the integral vanishes for odd $k$, we compute that

$$\int_{\mathbb{R}} (x - y)^{2N} g_\epsilon(y)^2 \, dy = \frac{4N!}{2\beta^N} \sum_{j=0}^{N-1} \frac{4^j \beta}{(N-j)(2j)!} x^{2j},$$

which yields the first result. The second statement then follows by induction from the observations that by the first identity

$$x^2 = (x^2 * g^2_\epsilon)(x) - \frac{1}{2\beta} \left((x^2 - 1/(2\beta)) * g^2_\epsilon\right)(x)$$

as well as

$$x^{2N} = (x^{2N} * g^2_\epsilon)(x) - p_N(x) = (x^{2N} * g^2_\epsilon)(x) - \sum_{j=0}^{N-1} \frac{1}{\beta^{(N-j)}} a_{N,j} x^{2j}.$$  

Since $g^2_\epsilon \geq 0$ and

$$|x - y|^{2N-\epsilon} \leq \max(2|x|, 2|y|)^{2N-\epsilon} \leq 2^{2N-\epsilon}(|x|^{2N-\epsilon} + |y|^{2N-\epsilon}),$$

we obtain the bound

$$\int_{\mathbb{R}} |x - y|^{2N-\epsilon} g_\epsilon(y)^2 \, dx \leq 2^{2N-\epsilon} \left(\int_{\mathbb{R}} |x|^{2N-\epsilon} + \int_{\mathbb{R}} |y|^{2N-\epsilon} g_\epsilon(y)^2 \, dy\right)$$

which yields the claimed inequality. Finally, since $x \mapsto |x|^{2N-\epsilon}$ is a convex function for $0 < \epsilon < 2N - 1$ and $\|g_\epsilon\|_2 = 1$, we can apply Jensen’s inequality to obtain

$$\int_{\mathbb{R}} |x - y|^{2N-\epsilon} g_\epsilon(y)^2 \, dy \geq \left(\int_{\mathbb{R}} (x - y)g_\epsilon(y)^2 \, dy\right)^{2N-\epsilon} = |x|^{2N-\epsilon}. \quad \square$$

A. Lower bound on the Riesz mean

In Ref. 6, a lower bound on the eigenvalues of a general class of operators on sets of finite measure with Neumann boundary condition was proved by means of an argument that relied on the Fourier transform. Here, we use a similar approach, with the coherent state transform replacing the Fourier transform.

Let $\psi_j^W$ denote the orthonormal eigenfunctions corresponding to the eigenvalues $\lambda_j^W$ of the operator $H_0 + W$ satisfying the assumptions in Proposition 1. They form a complete set of the Hilbert space $L^2(\mathbb{R})$, and by Plancherel’s theorem, it holds that

$$\iint_{\mathbb{R}^2} |\psi_j^W(k, y)|^2 \, dk \, dy = \|\psi_j^W\|_2^2 = 1. \quad (5)$$

We can thus write

$$\sum_{j \geq 1} (\lambda - \lambda_j^W) = \sum_{j \geq 1} (\lambda - \lambda_j^W), \iint_{\mathbb{R}^2} |\psi_j(k, y)|^2 \, dk \, dy,$$

and inserting the definition (4)

$$\sum_{j \geq 1} (\lambda - \lambda_j^W) = \iint_{\mathbb{R}^2} \sum_{j \geq 1} (\lambda - \lambda_j^W)(\psi_j^W, e_{k, y})(\psi_j^W, e_{k, y}) \, dk \, dy$$

and

$$\iint_{\mathbb{R}^2} \sum_{j \geq 1} (\lambda - \lambda_j^W)(e_{k, y}, \psi_j^W)(e_{k, y}, \psi_j^W) \, dk \, dy.$$
We can replace the sum by an integral with respect to the projection-valued measure \( dE^W_\mu \) for \( H_0 + W \) on \( \mathbb{R} \) as

\[
\sum_{j \geq 1} (\lambda - \lambda_j^W)_+ = \int_{\mathbb{R}} \int_{\mathbb{R}} (\lambda - \mu)_+ (dE^W_\mu e_{k,y}, e_{k,y}) \, dk \, dy.
\]

By the spectral theorem,

\[
\int_{\mathbb{R}} (dE^W_\mu e_{k,y}, e_{k,y}) = (e_{k,y}, e_{k,y}) = |g|^2 = 1,
\]

and thus we can apply Jensen’s inequality with the convex function \( x \mapsto (\lambda - x)_+ \) to obtain the lower bound

\[
\sum_{j \geq 1} (\lambda - \lambda_j^W)_+ \geq \int_{\mathbb{R}} \int_{\mathbb{R}} (\lambda - \mu)_+ (dE^W_\mu e_{k,y}, e_{k,y}) \, dk \, dy.
\]

Finally, by the spectral theorem, the inner integral is

\[
\int_{\mathbb{R}} \mu(dE^W_\mu e_{k,y}, e_{k,y}) = \langle H_0 e_{k,y}, e_{k,y} \rangle + \langle W e_{k,y}, e_{k,y} \rangle.
\]

Following Ref. 8, we know

\[
\langle H_0 e_{k,y}, e_{k,y} \rangle = \frac{1}{d_y^2} 2 \cosh(2\pi \beta x)
\]

and we compute

\[
\langle W e_{k,y}, e_{k,y} \rangle = \int_{\mathbb{R}} W(x)(x)^2 \, dx = W_\beta(y).
\]

Combining these two results with (6), we arrive at

\[
\sum_{j \geq 1} (\lambda - \lambda_j^W)_+ \geq \int_{\mathbb{R}} \left( \lambda - \frac{1}{d_y^2} 2 \cosh(2\pi \beta x) - W_\beta(y) \right) \, dk \, dy.
\]

**B. Lower bound for hyperbolic cosine potential**

Let \( \lambda \) be the eigenvalues of \( H_0 + 2 \cosh(2\pi \beta x) \). In this special case, which was considered in Ref. 8, one obtains from the computations above with \( W(x) = 2 \cosh(2\pi \beta x) \) and from Proposition 8 that

\[
\sum_{j \geq 1} (\lambda - \lambda_j^W)_+ \geq \int_{\mathbb{R}} \left( \lambda - \frac{1}{d_y^2} 2 \cosh(2\pi \beta x) - \frac{1}{\epsilon_y} 2 \cosh(2\pi \beta y) \right) \, dk \, dy.
\]

By (2), the asymptotic behavior of this lower bound does not depend on \( \epsilon_y, d_y \) and is of the desired form.

**C. Lower bound for polynomial potential**

Let \( \lambda \) be the eigenvalues of \( H_0 + x^{2N} + r(x) \). By the min-max principle, we obtain a lower bound on the Riesz mean if we replace \( x^{2N} + r(x) \) by the larger potential \( x^{2N} + C(1 + |x|^{2N-\epsilon}) \). Using the computations above with \( W(x) = x^{2N} + C(1 + |x|^{2N-\epsilon}) \) together with Proposition 9 and the fact that for some \( 0 < \delta \leq \varepsilon \) both \( |p_N(y)/(1 + |y|^{2N-\delta}) | \) and \( (1 + |y|^{2N-\epsilon})/(1 + |y|^{2N-\delta}) \) are bounded yields

\[
\sum_{j \geq 1} (\lambda - \lambda_j^W)_+ \geq \int_{\mathbb{R}} \left( \lambda - \frac{1}{d_y^2} 2 \cosh(2\pi \beta x) - y^{2N} - C_N (1 + |y|^{2N-\delta}) \right) \, dk \, dy
\]

for some constant \( C_N \) depending on \( \beta \). By (3) the asymptotic behavior of this lower bound does not depend on \( C_N, d_y \) and is of the desired form.
D. Upper bound on the Riesz mean

Again, we will use a similar approach to Ref. 6, where an upper bound on the eigenvalues of a general class of operators on sets of finite measure with Dirichlet boundary condition was proved.

Let $W$ be a potential that satisfies the assumptions of Proposition 1. Consider the eigenvalues $\lambda_j^W$ of $H_0 + W_\delta$ where $W_\delta = W * \delta^2$ and let $\psi_j^W$ be the corresponding orthonormal eigenfunctions. Using the Karamata–Tauberian theorem (see, e.g., Ref. 12, Theorem 10.3) in a version that allows for logarithmic factors (see, e.g., Ref. 11). The second form.

With a constant $C$.

Proposition 9, we may further decrease this potential to $W_\beta$.

E. Upper bound for hyperbolic cosine potential

Let $\lambda_j$ be the eigenvalues of $H_0 + 2 \cosh(2\pi bx)$. In this special case, which was considered in Ref. 8, we can choose $W(x) = \epsilon_\beta 2 \cosh(2\pi bx)$ such that $W_\beta(x) = 2 \cosh(2\pi bx)$ by Proposition 8. The computation above then yields

$$\sum_{j=1}^{\infty} (\lambda - \lambda_j^W), \leq \int_{\mathbb{R}} (1 - \epsilon_\beta 2 \cosh(2\pi bx) - W(y)) dy.$$ 

By (2), the asymptotic behavior of this upper bound does not depend on $\epsilon_\beta, \delta_\beta$ and is of the desired form.

F. Upper bound for polynomial potential

Let $\lambda_j$ be the eigenvalues of $H_0 + x^{2N} + r(x)$. By the min-max principle, we obtain an upper bound on the Riesz mean if we replace $x^{2N} + r(x)$ by the smaller potential $x^{2N} - C(1 + |x|^{2N-\epsilon})$. Applying again the min-max principle together with the last statement in Proposition 9, we may further decrease this potential to $x^{2N} - C(1 + |x|^{2N-\epsilon} * \delta^2)(x)$. By Proposition 9, this potential coincides with $W_\beta$ for the choice $W(x) = x^{2N} + q_N(x) - C(1 + |x|^{2N-\epsilon})$. The computation above and the fact that for some $0 < \delta \leq \epsilon$ both $|q_N(y)/(1 + |y|^{2N-\epsilon})$ and $(1 + |y|^{2N-\epsilon})/(1 + |y|^{2N-\delta})$ are bounded yields

$$\sum_{j=1}^{\infty} (\lambda - \lambda_j), \leq \int_{\mathbb{R}} (1 - \epsilon_\beta 2 \cosh(2\pi bx) - y^{2N} + C_N(1 + |y|^{2N-\delta})) dy$$

with a constant $C_N$ depending on $\beta$. By (3), the asymptotic behavior of this upper bound does not depend on $C_N, \delta_\beta$ and is of the desired form.

IV. THE PROOF OF COROLLARIES 3 AND 5

In Ref. 8, we provided two proofs of Corollary 3. The first one made use of an observation in Ref. 7 that allows us to obtain asymptotics of the traces of convex functions of self-adjoint operators from the behavior of their Riesz means. The result is then a consequence of the Karamata–Tauberian theorem (see, e.g., Ref. 12, Theorem 10.3) in a version that allows for logarithmic factors (see, e.g., Ref. 11). The second proof used a more direct approach in estimating the number of eigenvalues below a given value by Riesz means. Here, we present a proof that is in spirit very close to the latter argument, but emphasizes the role of convexity. The proof method has been used in Ref. 1 in a similar context to our work, but has also been applied previously in a nonlinear setting by Lieb and Simon, who give reference to Griffiths’ for emphasising its use in mathematical physics.
Again, assume that $W$ satisfies the assumptions of Proposition 1 and let $\lambda_j^W$ denote the discrete eigenvalues of $H_0 + W$. Note that for any $h > 0$,

$$\sum_{j \geq 1} (\lambda - \lambda_j^W)_+ \leq \sum_{j \geq 1} (\lambda + h - \lambda_j^W)_+ - hN^W(\lambda),$$

where $N^W(\lambda)$ denotes the number of eigenvalues $\lambda_j^W$ below $\lambda$. As a consequence, we obtain the upper bound

$$N^W(\lambda) \leq \frac{1}{h} \left( \sum_{j \geq 1} (\lambda + h - \lambda_j^W)_+ - \sum_{j \geq 1} (\lambda - \lambda_j^W)_+ \right). \quad (7)$$

To obtain a lower bound, we observe that similarly

$$N^W(\lambda) \geq \frac{1}{h} \left( \sum_{j \geq 1} (\lambda - \lambda_j^W)_+ - \sum_{j \geq 1} (\lambda - \lambda_j^W)_+ \right). \quad (8)$$

**A. Proof for hyperbolic cosine potential**

The result can be proved analogously to the case of polynomial potentials, for which details are presented below.

**B. Proof for polynomial potential**

Let $\lambda_j$ be the eigenvalues of $H_0 + x^{2N} + r(x)$. By Theorem 4, there are constants $C_1, C_2$ such that

$$\sum_{j \geq 1} (\lambda - \lambda_j)_+ \leq \frac{2}{\pi b} \left( \frac{2N}{2N + 1} \log \lambda + C_1 \frac{\lambda^{2N+1}}{\lambda^{2N}} \right)$$

and

$$\sum_{j \geq 1} (\lambda - \lambda_j)_+ \geq \frac{2}{\pi b} \left( \frac{2N}{2N + 1} \log \lambda + C_2 \frac{\lambda^{2N+1}}{\lambda^{2N}} \right)$$

for all sufficiently large $\lambda$. Inserting these bounds into (7) and noting that due to the convexity of the function $f(x) = x^{2N} \log x$ for $x > 1$ necessarily $f(\lambda + h) - f(\lambda) \leq hf'(\lambda + h)$, we obtain the upper bound

$$\frac{N(\lambda)}{\frac{2}{\pi b} \lambda^{2N+1} \log \lambda} \leq \frac{(\lambda + h)^{2N} \log(\lambda + h) + 2N}{\lambda^{2N+1} (\lambda + h)^{2N}} \frac{\lambda^{2N+1}}{\lambda^{2N}} \log \lambda + C_1 \frac{\lambda^{2N+1}}{\lambda^{2N}} - C_2 \frac{\lambda^{2N+1}}{\lambda^{2N}}.$$
ACKNOWLEDGMENTS

L.S. was supported by VILLUM FONDEN through the QMATH Centre of Excellence (Grant No. 10059). L.S. would like to thank the organizers of the program Spectral Methods in Mathematical Physics for their hospitality at the Institut Mittag-Leffler where this manuscript was being completed. A.L. was supported by RSF Grant No. 18-11-00032.

REFERENCES