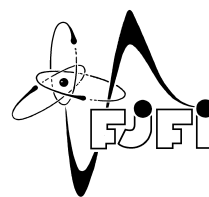




CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Nuclear Sciences and Physical Engineering
Department of Mathematics



Optimal discrete Hardy inequalities of higher order

Optimální diskrétní Hardyho nerovnosti vyšších řádů

Master's Thesis

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Pokyny pro vypracování:

- 1) Zobecněním teorie z článku [6] formulujte a dokažte postačující podmínky pro generování a optimalitu diskrétních p -Hardyho nerovností vyššího řádu pro obecné $p > 1$ a celočíselnou mocninu diskrétního Laplaceova operátoru.
- 2) Aplikujte abstraktní výsledky z bodu (1) na konkrétní případy a odvoďte nové explicitní optimální nerovnosti.
- 3) Zobecněním teorie z článku [6] formulujte a dokažte postačující podmínky pro generování a optimalitu diskrétních Hardyho nerovností vyššího řádu pro $p=2$ a obecnou mocninu diskrétního Laplaceova operátoru.
- 4) Aplikujte abstraktní výsledky z bodu (3) na konkrétní případy a odvoďte nové explicitní optimální nerovnosti.

Seznam doporučené literatury:

- [1] F. Fischer, Hardy Inequalities on Graphs. Doctoral dissertation, Universitat Potsdam, 2024.
- [2] F. Fischer, M. Keller, F. Pogorzelski, An improved discrete p -Hardy inequality, Integral Equations Operator Theory 95, 4 (2023).
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V Praze dne 17.04.2026

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.....
podpis studenta

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Author's declaration:

I declare that this Master's Thesis is entirely my own work, and I have listed all the used sources in the bibliography. In addition, I confirm that the available AI tools were used solely for grammar check and improving sentence formulations, in full accordance with the guidelines set out by CTU in Prague.

Prague, April 23, 2026

Bc. Jakub Waclawek

Název práce:

Optimální diskrétní Hardyho nerovnosti vyšších řádů

Autor: Bc. Jakub Waclawek

Studijní program: Aplikovaná algebra a analýza

Druh práce: Diplomová práce

Vedoucí práce: doc. Ing. František Štampach, Ph.D., Katedra matematiky

Abstrakt: Tato práce se věnuje studiu optimálních Hardyho nerovností vyššího řádu na polopřímce, které poskytují dolní odhady pro normy diskrétních derivací. Existující výsledky rozšíříme na nelineární p -Hardyho nerovnosti a na nerovnosti Hardyho typu pro neceločíselné mocniny Laplaceova operátoru. V obou případech zformulujeme obecnou metodu pro konstrukci nerovností libovolného řádu. Nalezneme postačující podmínky, za kterých parametrická posloupnost generuje (optimální) Hardyho váhy, a konkrétní volbou této posloupnosti získáme nové explicitní optimální p -Hardyho a zlomkové Hardyho váhy. Odhadem těchto optimálních vah odvodíme klasické p -Hardyho a zlomkové Hardyho nerovnosti libovolného řádu.

Klíčová slova: diskrétní p -Birmanova nerovnost, diskrétní p -Hardyho nerovnost, Hardyho nerovnost, optimální Hardyho váhy, zlomková Hardyho nerovnost

Title:

Optimal discrete Hardy inequalities of higher order

Author: Bc. Jakub Waclawek

Abstract: This thesis is devoted to the study of optimal Hardy inequalities of higher order on the half-line, which provide lower bounds for the norms of discrete derivatives. We extend existing results to the nonlinear setting of p -Hardy inequalities and to Hardy-type inequalities for non-integer powers of the Laplace operator. In both cases, we develop a general method for constructing inequalities of arbitrary order. We derive sufficient conditions under which a parameter sequence generates (optimal) Hardy weights and, for suitable choices of this sequence, we obtain new explicit optimal p -Hardy and fractional Hardy weights. Furthermore, by establishing appropriate lower bounds for these optimal weights, we recover the classical p -Hardy and fractional Hardy inequalities of arbitrary order.

Key words: discrete p -Birman inequality, discrete p -Hardy inequality, fractional Hardy inequality, Hardy inequality, optimal Hardy weights

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Introduction

In 1915, the renowned English mathematician Godfrey Harold Hardy published one of his most famous theorems. While seeking an elementary proof of the *Hilbert inequality*,

$$\sum_{n,m=1}^{\infty} \frac{a_m a_n}{m+n} \leq \pi \sum_{n=1}^{\infty} a_n^2,$$

which holds for all non-negative square-summable sequences $a \in \ell^2(\mathbb{N})$, he unexpectedly uncovered a remarkable fact: the convergence of the series $\sum_{n=1}^{\infty} a_n^2$ implies the convergence of the series of squared cumulative averages $\sum_{n=1}^{\infty} (A_n/n)^2$, where $A_n := \sum_{k=1}^n a_k$. Now, for more than a century, this result has been widely recognized as the weak form of the *discrete Hardy inequality*.

Following Hardy's groundbreaking discovery, several leading mathematicians joined him in exploring and advancing this beautiful field of mathematics. Among the first was E. Landau, who, in 1921, extended the discrete Hardy inequality from sequences in ℓ^2 to those in ℓ^p for an arbitrary exponent $p > 1$. Namely, denoting $a_n := u_n - u_{n-1}$, for any finitely supported complex sequence $u \in C_0(\mathbb{N})$ with $u_0 := 0$, he established the *discrete p -Hardy inequality*

$$\sum_{n=1}^{\infty} |u_n - u_{n-1}|^p \geq \left(\frac{p-1}{p} \right)^p \sum_{n=1}^{\infty} \frac{|u_n|^p}{n^p} \quad (1)$$

along with the optimality of the constant on the right-hand side.

Shortly after, in 1924, Hardy formulated the well-known continuous form of the Hardy inequality, which reads

$$\int_0^{\infty} |\varphi'(x)|^p dx \geq \left(\frac{p-1}{p} \right)^p \int_0^{\infty} \frac{|\varphi(x)|^p}{x^p} dx \quad (2)$$

and holds for all smooth functions $\varphi \in C_0^{\infty}(\mathbb{R}_+)$ compactly supported in $\mathbb{R}_+ := (0, \infty)$. We refer the reader to [29, 30] for more historical details and proofs of inequalities (1) and (2).

Given the wide range of applications of the Hardy inequality in probability theory, the theory of partial differential equations, and numerous other domains, its various generalizations have been the subject of extensive investigation. Most research has focused on the linear case $p = 2$ where inequalities (1) and (2) represent lower bounds on the discrete and continuous Dirichlet Laplacians on the half-line in the sense of quadratic forms. In the context of the present work, we focus on higher-order variants of inequalities (1) and (2), which we refer to as the *Birman inequalities* or the *Hardy inequalities of higher order*. In 1961, Birman [4] generalized inequality (2), with $p = 2$, to higher-order derivatives:

$$\int_0^{\infty} |\varphi^{(\ell)}(x)|^2 dx \geq \left(\frac{1}{2} \right)_{\ell}^2 \int_0^{\infty} \frac{|\varphi(x)|^2}{x^{2\ell}} dx, \quad (3)$$

where $\varphi \in C_0^{\infty}(\mathbb{R}_+)$, $\ell \in \mathbb{N}$, and $(\nu)_{\ell} := \nu(\nu+1) \cdots (\nu+\ell-1)$ denotes the Pochhammer symbol for any $\nu \in \mathbb{R}$. A proof of (3), together with the optimality of the constant, can be found in [35]; see also the recent paper [20] for other proofs and generalizations. The particular case $\ell = 2$ of (3) was discovered earlier by Rellich [36], even in higher dimensions, and is commonly referred to as the *Rellich inequality*.

Surprisingly, the discrete version of (3) was proven only recently in [24]. For any $\ell \in \mathbb{N}$ and $u \in C_0(\mathbb{N})$ with $u_n = 0$ for all $n < \ell$, the authors found the *discrete Birman inequality*

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^2 \geq \left(\frac{1}{2}\right)_\ell^2 \sum_{n=\ell}^{\infty} \frac{|u_n|^2}{n^{2\ell}}, \quad (4)$$

where the *discrete gradient* is defined as $\nabla u_n := u_n - u_{n-1}$ for all $n \geq 1$ with the convention $u_0 := 0$; see Section 1.1 for details about the notation of discrete difference operators. The optimality of the constant on the right-hand side was proven therein.

The key idea behind their proof of the optimality relies on an interesting observation: assuming the discrete Hardy (or even Birman) inequality (1), one may derive its continuous version (2). Similarly, as E. Landau already noted in 1921, by examining a suitable step function, an integral version of the continuous Hardy inequality leads to the corresponding discrete inequality. This equivalence renders the following discrepancy between the two versions all the more intriguing.

It is a well-known fact that the classical Hardy weight $1/(4x^2)$ in the first-order continuous Hardy inequality

$$\int_0^\infty |\varphi'(x)|^2 dx \geq \frac{1}{4} \int_0^\infty \frac{|\varphi(x)|^2}{x^2} dx \quad (5)$$

is *critical*. This means that if (5) holds for all test functions $\varphi \in C_0^\infty(\mathbb{R}_+)$ with $1/(4x^2)$ replaced by a measurable function $\rho(x) \geq 1/(4x^2)$ for a.e. $x > 0$, then, necessarily, $\rho(x) = 1/(4x^2)$ for a.e. $x > 0$. In contrast, the opposite was found to be true in the discrete setting. In [26], M. Keller, Y. Pinchover, and F. Pogorzelski proved the discrete Hardy inequality

$$\sum_{n=1}^{\infty} |\nabla u_n|^2 \geq \sum_{n=1}^{\infty} \rho_n^{\text{KPP}} |u_n|^2, \quad (6)$$

for all $u \in C_0(\mathbb{N})$ with $u_0 := 0$, where the improved weight is given by the formula

$$\rho_n^{\text{KPP}} := 2 - \sqrt{\frac{n-1}{n}} - \sqrt{\frac{n+1}{n}} > \frac{1}{4n^2}$$

for all $n \in \mathbb{N}$. Additionally, the authors proved in [27] that the weight ρ^{KPP} is *null-critical* (see Remark 1.2 for the definition), which, in particular, implies that the weight is *critical*, i.e. that it cannot be further improved by a pointwise bigger sequence. This result was subsequently extended to an arbitrary exponent $p > 1$ within the dissertation of F. Fisher [15], namely, in the article [17] coauthored with M. Keller and F. Pogorzelski, where the p -Hardy inequality

$$\sum_{n=1}^{\infty} |u_n - u_{n-1}|^p \geq \sum_{n=1}^{\infty} \rho_n^{\text{FKP}} |u_n|^p, \quad (7)$$

with the null-critical weight

$$\rho_n^{\text{FKP}} := \left(1 - \left(1 - \frac{1}{n}\right)^{1-1/p}\right)^{p-1} - \left(\left(1 + \frac{1}{n}\right)^{1-1/p} - 1\right)^{p-1} > \left(\frac{p-1}{p}\right)^p \frac{1}{n^p} \quad (8)$$

was verified for all real-valued $u \in C_0(\mathbb{N})$ with $u_0 := 0$.

Naturally, it was expected that even the higher-order discrete Hardy inequalities (4) admit an improvement analogous to (6). Initially, some refinements were made in the Rellich case $\ell = 2$ in [24, 19], and later the hypothesis was confirmed in full generality in [43], where we established the *optimal* discrete Hardy inequality of an arbitrary order $\ell \in \mathbb{N}$:

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^2 \geq \sum_{n=\ell}^{\infty} \rho_\ell^{\text{SW}}(n) |u_n|^2 \quad (9)$$

for all $u \in C_0(\mathbb{N})$ with $u_n = 0$ for all $n < \ell$, where the weights are given by the formulas

$$\rho_\ell^{\text{SW}}(n) := \frac{(-\Delta)^\ell \mathfrak{g}_\ell^{\text{SW}}(n)}{\mathfrak{g}_\ell^{\text{SW}}(n)}, \quad \text{for all } n \geq \ell, \quad \text{and} \quad \mathfrak{g}_\ell^{\text{SW}}(n) := \sqrt{n} \prod_{j=1}^{\ell-1} (n-j), \quad \text{for all } n \geq 0. \quad (10)$$

Here the *discrete Laplacian* is defined as $\Delta u_n := u_{n-1} - 2u_n + u_{n+1}$; see also Section 1.1. *Optimality* is a rather strong property (see Definition 1.1), which, in particular, entails null-criticality and hence criticality of the Hardy weight under consideration.

In this thesis, we obtain new results in two rather unexplored directions within the theory of discrete Hardy-type inequalities:

- In Chapter 1, we study p -generalizations of the discrete Birman inequalities (4) and (9) for arbitrary $p > 1$. Building on the approach of [43], where only the more tractable linear case $p = 2$ was considered, optimal p -Hardy inequalities of any order $\ell \in \mathbb{N}$ are derived in Sections 1.2 and 1.3. The classical higher-order p -Hardy inequality is established in Section 1.4.
- In Chapter 2, we once more restrict our attention to the linear case $p = 2$. We reformulate the discrete Birman inequalities (4) and (9) in the sense of quadratic forms as the lower bounds $(-\Delta)^\ell \geq \rho$, where ρ stands for the operator of multiplication by a given Birman weight ρ . Using spectral representation of the positive self-adjoint operator $-\Delta$, we define its general positive powers and derive analogous estimates

$$(-\Delta)^\alpha \geq \rho$$

for any $\alpha > 0$, answering the questions raised in [43, Section 1.4].

Chapter 1

p -Hardy inequalities of higher order

For $p = 2$, Hardy inequalities of arbitrary order $\ell \in \mathbb{N}$

$$\int_0^\infty |\varphi^{(\ell)}(x)|^2 dx \geq \left(\frac{1}{2}\right)_\ell^2 \int_0^\infty \frac{|\varphi(x)|^2}{x^{2\ell}} dx, \quad \text{resp.} \quad \sum_{n=\ell}^\infty |\nabla^\ell u_n|^2 \geq \left(\frac{1}{2}\right)_\ell^2 \sum_{n=\ell}^\infty \frac{|u_n|^2}{n^{2\ell}},$$

valid for all $\varphi \in C_0^\infty(\mathbb{R}_+)$, resp. all $u \in C_0(\mathbb{N})$ with $u_n = 0$ for all $n < \ell$, are well-established classical results proved, for instance, in [4, 24]. See also [35] for a generalization of the continuous Birman inequality to higher dimensions.

In contrast, the nonlinear case $p \neq 2$ is significantly less developed in the existing literature. Although the continuous p -Hardy inequality of order ℓ ,

$$\int_0^\infty |\varphi^{(\ell)}(x)|^p dx \geq \left(\frac{p-1}{p}\right)_\ell^p \int_0^\infty \frac{|\varphi(x)|^p}{x^{\ell p}} dx, \quad (1.1)$$

which holds for all $p > 1$ and all $\varphi \in C_0^\infty(\mathbb{R}_+)$, is well-known among experts, we have been unable to identify a reference in which this statement is formulated explicitly, with the exception of the particular case $\ell = 2$, corresponding to the p -Rellich inequality, which appears in [35, Eq. (1.2)]. At an implicit level, inequality (1.1) can be traced back to the classical work of Hardy, Littlewood, and Pólya [22]; see Remark 1.49. Related results in higher dimensions can also be found in [12].

Furthermore, an essential component of the framework is currently missing, leaving the theory of Hardy inequalities on the half-line incomplete: the discrete p -Hardy inequalities of higher order. The primary objective of this chapter is to address this gap by establishing and further analyzing new explicit discrete p -Birman inequalities.

This chapter is structured as follows:

- In Section 1.1, we introduce the necessary notation and compare it with the conventions adopted in recent works [28, 24, 43] on Hardy-type inequalities.
- In Section 1.2, we extend our results from the paper [43] to the general case $p > 1$. Through Theorems 1.7, 1.9, and 1.10, we develop a method to construct abstract p -Birman weights in terms of a parameter sequence $\mathbf{g}$ subject to suitable monotonicity and growth conditions.
- In Section 1.3, we apply the results of Section 1.2 to the parameter sequences $\mathbf{g}^{(\ell,p)}$ and $\tilde{\mathbf{g}}^{(\ell,p)}$, as defined in (1.18) and (1.19) respectively, and obtain explicit optimal p -Hardy weights of an arbitrary order.
- In Section 1.4, we establish classical discrete p -Birman inequalities, which constitute direct discrete analogs of the continuous inequality (1.1) and show that the optimal weights $\rho^{(\ell,p)}$, introduced in Section 1.3, improve upon the corresponding classical weights. Finally, in Section 1.4.3, we present a new proof of the continuous result by recovering it as a limiting case of its discrete analog.

1.1 Notation of discrete difference operators

The notation of discrete difference operators used in papers studying discrete Hardy inequalities [28, 24, 43] varies, and therefore it may cause confusion for a non-specialized reader. In this section, our aim is to clarify, but mainly unify, the miscellaneous conventions.

First, let us consider the Hilbert space of square-summable sequences $\ell^2(\mathbb{N})$ indexed by natural numbers $\mathbb{N} := \{1, 2, \dots\}$, and its standard basis $\{\delta_n\}_{n=1}^\infty$ defined as

$$(\delta_n)_m := \delta_{nm} = \begin{cases} 0 & \text{if } n \neq m, \\ 1 & \text{if } n = m, \end{cases} \quad \text{for all } m, n \in \mathbb{N},$$

where δ is the Kronecker delta. On this space, we define the *discrete gradient* and *divergence* by the formulas

$$\nabla u_n := \begin{cases} u_n - u_{n-1} & \text{if } n \geq 2, \\ u_1 & \text{if } n = 1, \end{cases} \quad \text{and} \quad \operatorname{div} u_n := u_{n+1} - u_n \quad \text{for all } n \in \mathbb{N}.$$

Furthermore, the *discrete Laplacian* on $\ell^2(\mathbb{N})$ is then given by the familiar formula $\Delta_{\mathbb{N}} := \operatorname{div} \nabla$ (we shall omit $\circ$ when composing difference operators for concise notation), i.e.

$$(\Delta_{\mathbb{N}} u)_n := \begin{cases} u_{n-1} - 2u_n + u_{n+1} & \text{if } n \geq 2, \\ -2u_1 + u_2 & \text{if } n = 1. \end{cases}$$

The index $\mathbb{N}$ is used to distinguish the operator from the Laplace operator used in the rest of the text, defined below by the formula (1.5). The operator $-\Delta_{\mathbb{N}}$ also coincides with the *graph Laplacian* associated with the standard graph structure on $\mathbb{N}$, which was studied in [28]. Notice that on the Hilbert space $\ell^2(\mathbb{N})$ endowed with the Euclidean inner product, the adjoint of the discrete gradient is $\nabla^* = -\operatorname{div}$, hence $-\Delta_{\mathbb{N}} = \nabla^* \nabla$ is a positive self-adjoint operator.

In [24], the authors defined the half-integer powers of the Laplace operator as

$$(-\Delta_{\mathbb{N}})^{\ell/2} := \begin{cases} (-\Delta_{\mathbb{N}})^m & \text{if } \ell = 2m \in 2\mathbb{N}, \\ \nabla(-\Delta_{\mathbb{N}})^m & \text{if } \ell = 2m + 1 \in 2\mathbb{N}_0 + 1, \end{cases}$$

and considered Hardy inequalities of higher order (4) in the form

$$\sum_{n=\lceil \ell/2 \rceil}^{\infty} |(-\Delta_{\mathbb{N}})^{\ell/2} u_n|^2 \geq \left(\frac{1}{2}\right)_{\ell}^2 \sum_{n=\ell}^{\infty} \frac{|u_n|^2}{n^{2\ell}}, \quad (1.2)$$

for all $u \in \ell^2(\mathbb{N})$ satisfying $u_n = 0$ for all $n < \ell$, where $\lceil \nu \rceil$ stands for the smallest integer greater than or equal to $\nu \in \mathbb{R}$. With this convention, the left-hand side can be rewritten as the quadratic form of the operator $(-\Delta_{\mathbb{N}})^{\ell}$ since

$$\sum_{n=\lceil \ell/2 \rceil}^{\infty} |(-\Delta_{\mathbb{N}})^{\ell/2} u_n|^2 = \|(-\Delta_{\mathbb{N}})^{\ell/2} u\|^2 = \langle u, ((-\Delta_{\mathbb{N}})^{\ell/2})^* (-\Delta_{\mathbb{N}})^{\ell/2} u \rangle = \langle u, (-\Delta_{\mathbb{N}})^{\ell} u \rangle.$$

Therefore, the inequality (1.2) amounts to the lower bound

$$(-\Delta_{\mathbb{N}})^{\ell} \geq \rho^B \quad \text{on the subspace } \{\delta_1, \dots, \delta_{\ell-1}\}^{\perp} \subset \ell^2(\mathbb{N}), \quad (1.3)$$

where ρ^B stands for the operator of multiplication by the classical Birman weight ρ^B given by the right-hand side of (1.2).

On the other hand, we will use the notation that utilizes solely the discrete gradient, where the left-hand side of the Birman inequality (4) reads

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^2 = \|\nabla^\ell u\|^2 = \langle u, (-1)^\ell \operatorname{div}^\ell \nabla^\ell u \rangle.$$

The Birman inequality then takes the form

$$(-1)^\ell \operatorname{div}^\ell \nabla^\ell \geq \rho^B \quad \text{on the subspace } \{\delta_1, \dots, \delta_{\ell-1}\}^\perp \subset \ell^2(\mathbb{N}). \quad (1.4)$$

It is important to emphasize the subtle differences between the operators $(-\Delta_{\mathbb{N}})^\ell$ and $(-1)^\ell \operatorname{div}^\ell \nabla^\ell$. While the matrix elements of $(-1)^\ell \operatorname{div}^\ell \nabla^\ell$ with respect to the standard basis can be straightforwardly computed as

$$\left((-1)^\ell \operatorname{div}^\ell \nabla^\ell \right)_{mn} = (-1)^{m+n} \binom{2\ell}{\ell + m - n} \quad \text{for all } m, n \in \mathbb{N},$$

and define a symmetric banded Toeplitz (i.e. diagonal-constant) matrix on $\ell^2(\mathbb{N})$, the matrix elements of $(-\Delta_{\mathbb{N}})^\ell$ are given in [18, Proposition 2.1] as

$$(-\Delta_{\mathbb{N}})_{mn}^\ell = (-1)^{m+n} \left[\binom{2\ell}{\ell + m - n} - \binom{2\ell}{\ell + m + n} \right] \quad \text{for all } m, n \in \mathbb{N}.$$

Observe that the operator $(-\Delta_{\mathbb{N}})^\ell$ is no longer Toeplitz and differs from $(-1)^\ell \operatorname{div}^\ell \nabla^\ell$ by an upper-left $(\ell-1) \times (\ell-1)$ Hankel matrix (i.e. a matrix with constant anti-diagonals). Nevertheless, the operators coincide on the subspace $\{\delta_1, \dots, \delta_{\ell-1}\}^\perp \subset \ell^2(\mathbb{N})$, thus rendering the inequalities (1.3) and (1.4) equivalent.

The operator $(-1)^\ell \operatorname{div}^\ell \nabla^\ell$ can also be interpreted as the restriction of the ℓ -th power of the discrete Laplacian defined on the Hilbert space $\ell^2(\mathbb{Z})$ by

$$(\Delta u)_n := u_{n-1} - 2u_n + u_{n+1} \quad \text{for all } n \in \mathbb{Z}. \quad (1.5)$$

Indeed, Proposition 2.2 yields the corresponding matrix representation with respect to the canonical basis $\{\delta_n\}_{n \in \mathbb{Z}}$ of $\ell^2(\mathbb{Z})$ in the form

$$(-\Delta)_{mn}^\ell = (-1)^{m+n} \binom{2\ell}{\ell + m - n} \quad \text{for all } m, n \in \mathbb{Z},$$

hence $(-\Delta)^\ell|_{\ell^2(\mathbb{N})} = (-1)^\ell \operatorname{div}^\ell \nabla^\ell$.

Keeping these considerations in mind, we formally extend the sequences in question by zero for negative indices and introduce the notation employed throughout this thesis, which is adopted from our work [43]. We denote by $C(\mathbb{Z})$ the space of all complex-valued sequences indexed by $\mathbb{Z}$ and, for each $\ell \in \mathbb{N}$, we define the subspace

$$H^\ell := \{u \in C(\mathbb{Z}) \mid u_n = 0 \text{ for all } n < \ell\}$$

and its subspaces

$$\mathcal{H}^{\ell,p} := H^\ell \cap \ell^p(\mathbb{Z}) \quad \text{and} \quad \mathcal{H}_0^\ell := H^\ell \cap C_0(\mathbb{Z}), \quad (1.6)$$

endowed with the ℓ^p -norm $\|\cdot\|_p$, where $C_0(\mathbb{Z})$ denotes the subspace of $C(\mathbb{Z})$ consisting of all finitely supported sequences. With a slight abuse of notation, we additionally introduce the *discrete gradient* and *discrete divergence* operators acting on $C(\mathbb{Z})$ as

$$(\nabla u)_n := u_n - u_{n-1} \quad \text{and} \quad (\operatorname{div} u)_n := u_{n+1} - u_n \quad (1.7)$$

for all $n \in \mathbb{Z}$. Since these operators commute on $C(\mathbb{Z})$, this convention simplifies subsequent arguments, as it obviates the need to specify the subspaces on which the identity $\operatorname{div} \nabla = \nabla \operatorname{div} = \Delta$ holds. We shall also make use of the *forward shift operator* S and the *middle operator* M defined on $C(\mathbb{Z})$ as

$$Su_n := u_{n+1} \quad \text{and} \quad Mu_n := \frac{u_{n+1} + u_n}{2} \quad (1.8)$$

for all $n \in \mathbb{Z}$. Note also that we have the operator identities $S^{-1}S = SS^{-1} = I$, $\operatorname{div} = S - I$, $\nabla = I - S^{-1}$, and therefore $\operatorname{div} = \nabla S = S \nabla$.

For $p \neq 2$, the absence of an inner product on $\ell^p(\mathbb{Z})$ makes it necessary to introduce further notation. Although the p -Birman inequalities cannot be interpreted in the sense of quadratic forms, it is nevertheless possible to *polarize* the ℓ^p -norm of $\nabla^\ell u$, for $u \in \mathcal{H}_0^\ell$, as

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p = \sum_{n=\ell}^{\infty} \overline{u_n} (-\Delta_p^{(\ell)} u)_n,$$

where the nonlinear p -Laplace operator of order $\ell \in \mathbb{N}$ is defined by

$$-\Delta_p^{(\ell)} := (-1)^\ell \operatorname{div}^\ell (\nabla^\ell \cdot)^{\langle p-1 \rangle} \quad \text{and} \quad -\Delta_p^{(0)} := (\cdot)^{\langle p-1 \rangle}. \quad (1.9)$$

Moreover, for streamlined notation, we set $\nu^{(\lambda)} := \nu |\nu|^{\lambda-1}$ for all $\nu \in \mathbb{C}$ and $\lambda > 0$, with the convention $0^{(\lambda)} = 0$.

1.2 Abstract optimal p -Birman inequalities

In this section, we explain how to construct p -Hardy weights of any order $\ell \in \mathbb{N}$ given a *parameter sequence* $\mathbf{g}$ that satisfies certain sufficient conditions. In fact, we slightly modify and extend the strategy from [43], where we considered the linear case $p = 2$, to the more involved general case with an arbitrary $p > 1$. Furthermore, we will discuss optimality of the acquired weights under stronger assumptions on the asymptotic behavior of $\mathbf{g}_n$ as $n \rightarrow \infty$.

We begin by presenting the main results of this chapter. To avoid distracting the reader and to maintain clarity, the corresponding proofs are postponed to Section 1.2.1. First, let us recall the definition of p -Hardy weights of higher order and their optimality, in accordance with [16] and [43].

Definition 1.1. Let $\ell \in \mathbb{N}$ and $p > 1$. A non-negative sequence $\{\rho_n\}_{n=\ell}^\infty$ is called a *discrete p -Hardy weight of order ℓ* (or *discrete p -Birman weight*) if and only if the *discrete p -Hardy inequality of order ℓ* (or *discrete p -Birman inequality*)

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p \geq \sum_{n=\ell}^{\infty} \rho_n |u_n|^p \quad (1.10)$$

holds for any $u \in \mathcal{H}_0^\ell$. In addition, the weight ρ is said to be *optimal* if it exhibits the following three properties:

- (i) *Criticality*: The weight ρ is called *critical* if for any p -Hardy weight $\tilde{\rho}$ of order ℓ , such that $\tilde{\rho}_n \geq \rho_n$ for all $n \geq \ell$, it follows that $\tilde{\rho} = \rho$.
- (ii) *Non-attainability*: The weight ρ is called *non-attainable* if, whenever the equality in (1.10) is attained for $u \in \mathcal{H}_0^\ell$ such that the right-hand side is finite, necessarily $u \equiv 0$.
- (iii) *Optimality near infinity*: The weight ρ is called *optimal near infinity* if for any $M \geq \ell$ and $\varepsilon > 0$ there exists $u \in \mathcal{H}_0^M$ such that

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p < (1 + \varepsilon) \sum_{n=\ell}^{\infty} \rho_n |u_n|^p.$$

Remark 1.2. We complement the three optimality properties with several explanatory remarks:

- (i) Criticality means that the p -Hardy weight enjoying this property cannot be further improved by a pointwise bigger sequence.
- (ii) The notion of non-attainability is not uniform in the existing literature. In [27], where first-order Hardy inequalities on graphs are investigated, the property that corresponds to the combination of criticality and non-attainability is referred to as *null-criticality*. Using the criticality theory for Schrödinger operators on discrete graphs, as developed in [28], the authors analyze whether the unique positive *generalized eigenvector* of the operator $-\Delta - \rho$, called the *Agmon ground state*, is, in fact, a genuine eigenvector. This definition was later extended to the ℓ^p setting in [16, 14]. Moreover, it was shown in [15, Theorem 11.2] that for certain p -Hardy weights, null-criticality also implies optimality near infinity. Nevertheless, it is evident that the notions of criticality and non-attainability employed in this thesis actually entail null-criticality and therefore constitute a stronger condition.

We additionally introduce a slightly weaker property, which we refer to as *non-attainability in $\mathcal{H}_0^\ell$* . Specifically, the weight ρ is said to be *non-attainable in $\mathcal{H}_0^\ell$* if, whenever equality in (1.10) is attained for $u \in \mathcal{H}_0^\ell$, necessarily $u \equiv 0$.

- (iii) Optimality near infinity means that the constant 1 appearing on the right-hand side of (1.10) cannot be further improved, even if we restrict ourselves only to the sequences from the space $\mathcal{H}_0^M \subset \mathcal{H}_0^\ell$ for any $M \geq \ell$. It is equivalent to the identity

$$\inf_{u \in \mathcal{H}_0^M \setminus \{0\}} \frac{\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p}{\sum_{n=\ell}^{\infty} \rho_n |u_n|^p} = 1 \quad \text{for all } M \geq \ell. \quad (1.11)$$

Let us also remark that optimality does not characterize the weight uniquely as was observed in [43], where we found infinitely many optimal Hardy weights of any order ℓ for $p = 2$.

Our starting point shall be a weighted generalization of an abstract first-order p -Hardy inequality analogous to [14, Theorem 3.1]. In [14], the authors study p -Hardy inequalities in an abstract graph setting for real-valued sequences. For our purposes, we consider their results for the standard line graph on $\mathbb{N}_0$. The proof of the weighted generalization is reminiscent of the one in [14] or [17, Proposition 4]. However, due to the non-triviality of the extension of the result to complex-valued sequences, it will be revisited in Section 1.2.1 nonetheless. The inequality is potentially of independent interest and will be employed to derive the Copson inequality (1.80) in Section 1.4.

Unless explicitly stated otherwise, we shall always assume $\ell \in \mathbb{N}$ and $p, q > 1$ to be Hölder conjugate exponents, i.e. they satisfy $1/p + 1/q = 1$, throughout what follows. Moreover, for two real numbers (or functions) α, β , we write $\alpha \lesssim \beta$ if and only if there exists a positive constant $C_p > 0$ such that $\alpha \leq C_p \beta$, where the constant C_p may depend only on p . We write $\alpha \approx \beta$ if and only if $\alpha \lesssim \beta \lesssim \alpha$.

Theorem 1.3. *Let $V \in C(\mathbb{N})$, such that $V_n \geq 0$ for all $n \geq 1$, and $\mathbf{g} \in H^1$, such that $\mathbf{g}_{n+1} \geq \mathbf{g}_n > 0$ for all $n \geq 1$. Then for any $u \in \mathcal{H}_0^1$, we have the inequalities*

$$\sum_{n=1}^{\infty} V_{n+1} \mathcal{R}(q; \mathbf{g}, u)_n \lesssim \sum_{n=1}^{\infty} V_n |\nabla u_n|^p + \sum_{n=1}^{\infty} \frac{\operatorname{div}(V(\nabla \mathbf{g})^{p-1})_n}{\mathbf{g}_n^{p-1}} |u_n|^p \lesssim \sum_{n=1}^{\infty} V_{n+1} \mathcal{R}(p; \mathbf{g}, u)_n \quad (1.12)$$

where the remainder terms are given by the formulas

$$\mathcal{R}(s; \mathbf{g}, u)_n := \begin{cases} \left| \sqrt{\frac{\mathbf{g}_n}{\mathbf{g}_{n+1}}} u_{n+1} - \sqrt{\frac{\mathbf{g}_{n+1}}{\mathbf{g}_n}} u_n \right|^p & \text{if } s \in (1, 2], \\ \left| \sqrt{\frac{\mathbf{g}_n}{\mathbf{g}_{n+1}}} u_{n+1} - \sqrt{\frac{\mathbf{g}_{n+1}}{\mathbf{g}_n}} u_n \right|^2 \left(|\operatorname{div} u_n| + \frac{|u_n|}{\mathbf{g}_n} \operatorname{div} \mathbf{g}_n \right)^{p-2} & \text{if } s \in (2, \infty), \end{cases} \quad (1.13)$$

for all $n \geq 1$, with the convention $0^{p-2} \equiv 0$ if $p \in (1, 2]$.

Remark 1.4. The parameter s appearing in the remainder terms, defined by (1.13), serves as an indicator specifying which of the two formulas is to be used for the lower and the upper bound in (1.12). Since the Hölder conjugate exponents $p, q > 1$ satisfy that $p > 2$ if and only if $q \in (1, 2)$, this notation encodes the fact that the two distinct remainder terms occurring on the left-hand and right-hand sides of the inequality (1.12) are interchanged when passing from the regime $p \in (1, 2)$ to the regime $p > 2$. The lower estimate in (1.12) asserts an abstract weighted p -Hardy inequality for any complex-valued sequence $u \in \mathcal{H}_0^1$. On the other hand, the upper estimate of (1.12) indicates how tight the inequality is, which will be essential later to derive the optimality of particular p -Hardy weights. Both estimates are rooted in the fundamental inequalities given by Lemma 1.13.

Remark 1.5. In the case $p = 2$, the inequalities in (1.12) hold as equalities with the implicit constants in the estimates $\lesssim$ being equal to 1. This is analogous to the results of [43, Theorem 0], which assert that for any $V \in C(\mathbb{N})$ and $\mathbf{g} \in H^1$, such that $\mathbf{g}_n > 0$ for all $n \geq 1$, we have the identity

$$\sum_{n=1}^{\infty} V_n |\nabla u_n|^2 + \sum_{n=1}^{\infty} \frac{\operatorname{div}(V \nabla \mathbf{g})_n}{\mathbf{g}_n} |u_n|^2 = \sum_{n=1}^{\infty} V_{n+1} \left| \sqrt{\frac{\mathbf{g}_n}{\mathbf{g}_{n+1}}} u_{n+1} - \sqrt{\frac{\mathbf{g}_{n+1}}{\mathbf{g}_n}} u_n \right|^2 \quad (1.14)$$

for all $u \in \mathcal{H}_0^1$. Note that the parameter sequence $\mathbf{g}$ is no longer required to be non-decreasing, nor is the potential V required to be non-negative.

Remark 1.6. The situation is less involved if only real-valued sequences are considered instead. In particular, if $V \in C(\mathbb{N})$, such that $V_n \geq 0$ for all $n \geq 1$, and $\mathbf{g} \in H^1$, such that $\mathbf{g}_n > 0$ for all $n \geq 1$ ($\mathbf{g}$ no longer has to be non-decreasing), we have the equivalence

$$\sum_{n=1}^{\infty} V_n |\nabla u_n|^p + \sum_{n=1}^{\infty} \frac{\operatorname{div}(V (\nabla \mathbf{g})^{\langle p-1 \rangle})_n}{\mathbf{g}_n^{p-1}} |u_n|^p \approx \sum_{n=1}^{\infty} V_{n+1} \tilde{\mathcal{R}}(\mathbf{g}, u)_n,$$

for all real-valued sequences $u \in \mathcal{H}_0^1$, where the remainder is given by the formula

$$\tilde{\mathcal{R}}(\mathbf{g}, u)_n := \left| \sqrt{\frac{\mathbf{g}_n}{\mathbf{g}_{n+1}}} u_{n+1} - \sqrt{\frac{\mathbf{g}_{n+1}}{\mathbf{g}_n}} u_n \right|^2 \left(\left| \sqrt{\frac{\mathbf{g}_n}{\mathbf{g}_{n+1}}} u_{n+1} - \sqrt{\frac{\mathbf{g}_{n+1}}{\mathbf{g}_n}} u_n \right| + M \left(\frac{|u_n|}{\mathbf{g}_n} \right) |\operatorname{div} \mathbf{g}_n| \right)^{p-2} \quad (1.15)$$

for all $p > 1$ and $n \geq 1$. The proof is analogous to the proof of Theorem 1.3 and is therefore omitted; see [14, Lemma 3.8, Eq. (3.9)] for the corresponding underlying inequality.

The weight V in inequality (1.12) enables an iterative procedure that yields analogous inequalities for higher-order difference operators. The key idea behind the derivation of such inequalities is a suitable selection of the parameter sequence $\mathbf{g}$ in each step of the iteration. In this way, we obtain convenient representations of the weights V in terms of $\mathbf{g}$, which, in turn, allows us to guarantee their non-negativity under additional assumptions imposed on $\mathbf{g}$.

Theorem 1.7. Suppose that $\mathbf{g} \in H^\ell$ satisfies the assumptions

$$\nabla^k \mathbf{g}_n > 0 \quad \text{for all } n \geq \ell \text{ and } k \in \{0, \dots, \ell\}, \quad (A1.1)$$

$$-\Delta_p^{(\ell-k)} \nabla^k \mathbf{g}_n \geq 0 \quad \text{for all } n \geq \ell \text{ and } k \in \{1, \dots, \ell-1\}. \quad (A1.2)$$

Then for all $u \in \mathcal{H}_0^\ell$, we have the inequalities

$$\sum_{k=1}^{\ell} R_k^{(\ell)}(q; \mathbf{g}, u) \lesssim \sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p - \sum_{n=\ell}^{\infty} \frac{-\Delta_p^{(\ell)} \mathbf{g}_n}{\mathbf{g}_n^{p-1}} |u_n|^p \lesssim \sum_{k=1}^{\ell} R_k^{(\ell)}(p; \mathbf{g}, u), \quad (1.16)$$

where the remainders are given by the formula

$$R_k^{(\ell)}(s; \mathbf{g}, u) := \sum_{n=\ell}^{\infty} \frac{-\Delta_p^{(\ell-k)} \nabla^k \mathbf{g}_{n+1}}{(\nabla^k \mathbf{g}_{n+1})^{p-1}} \mathcal{R}(s; \nabla^{k-1} \mathbf{g}, \nabla^{k-1} u)_n, \quad (1.17)$$

for all $k \in \{1, \dots, \ell\}$, with $\mathcal{R}(s; \mathbf{g}, u)$ defined by (1.13).

Remark 1.8. In view of Remark 1.6, for real-valued sequences, we may deduce an equivalence analogous to inequalities (1.16) with remainders corresponding to (1.15). Namely, for $\mathbf{g} \in H^\ell$ satisfying assumptions (A1.1) and (A1.2), we have the equivalence

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p - \sum_{n=\ell}^{\infty} \frac{-\Delta_p^{(\ell)} \mathbf{g}_n}{\mathbf{g}_n^{p-1}} |u_n|^p \asymp \sum_{k=1}^{\ell} \left[\sum_{n=\ell}^{\infty} \frac{-\Delta_p^{(\ell-k)} \nabla^k \mathbf{g}_{n+1}}{(\nabla^k \mathbf{g}_{n+1})^{p-1}} \tilde{\mathcal{R}}(\nabla^{k-1} \mathbf{g}, \nabla^{k-1} u)_n \right],$$

for all real-valued sequences $u \in \mathcal{H}_0^\ell$. The proof works along the lines of the proof of Theorem 1.7 in Section 1.2.1.2, hence it is omitted as well.

Let us further assume that the inequality in assumption (A1.2) holds for $k = 0$, that is, $-\Delta_p^{(\ell)} \mathbf{g}_n \geq 0$ for all $n \geq \ell$. Then

$$\rho(\mathbf{g}) := \frac{-\Delta_p^{(\ell)} \mathbf{g}}{\mathbf{g}^{p-1}}$$

defines a non-negative sequence in H^ℓ , and thus constitutes a p -Hardy weight of order ℓ . Moreover, we prove that this weight is non-attainable in $\mathcal{H}_0^\ell$; see Remark 1.2 for the definition.

Theorem 1.9. *Suppose that $\mathbf{g} \in H^\ell$ satisfies assumptions (A1.1), (A1.2), and, in addition,*

$$-\Delta_p^{(\ell)} \mathbf{g}_n \geq 0 \quad \text{for all } n \geq \ell. \quad (\text{A1.3})$$

Then $\rho(\mathbf{g}) = -\Delta_p^{(\ell)} \mathbf{g} / \mathbf{g}^{p-1}$ is a discrete p -Hardy weight of order ℓ , which is non-attainable in $\mathcal{H}_0^\ell$.

By imposing additional requirements on the asymptotic behavior of $\mathbf{g}_n$ as $n \rightarrow \infty$, and strict positivity in assumption (A1.3), we obtain sufficient conditions for the optimality of the discrete p -Hardy weights $\rho(\mathbf{g})$. We consider the following statement to be our first main result.

Theorem 1.10. *Suppose that $\mathbf{g} \in H^\ell$ satisfies assumptions (A1.1), (A1.2), and (A1.3) with strict positivity, i.e. $-\Delta_p^{(\ell)} \mathbf{g}_n > 0$ for all $n \geq \ell$. In addition, suppose that $\mathbf{g}$ admits the asymptotic expansion*

$$\mathbf{g}_n = \sum_{j=0}^{2\ell} \alpha_j n^{\ell-j-1/p} + \mathcal{O}(n^{-\ell-1-1/p}), \quad \text{as } n \rightarrow \infty, \text{ for some } \alpha_j \in \mathbb{R} \text{ with } \alpha_0 \neq 0. \quad (\text{A1.4})$$

Then the discrete p -Hardy weight $\rho(\mathbf{g}) = -\Delta_p^{(\ell)} \mathbf{g} / \mathbf{g}^{p-1}$ of order ℓ is optimal.

Remark 1.11. The strict positivity in assumption (A1.3) is required solely for the non-attainability of the weight $\rho(\mathbf{g})$, whereas the properties of criticality and optimality near infinity are already ensured by assumptions (A1.1)–(A1.4).

Remark 1.12. Without going into technical details, we note that the asymptotic expansion in (A1.4) can be replaced by one depending on a parameter $s \in (0, 1)$. The admissible range of s then determines which of the properties from the definition of optimality 1.1 are satisfied by the corresponding weight $\rho(\mathbf{g})$. Specifically, for $\mathbf{g} \in H^\ell$ subject to assumptions (A1.1), (A1.2), (A1.3) with strict positivity, and, in addition,

$$\mathbf{g}_n = \sum_{j=0}^{2\ell} \alpha_j n^{\ell-j-s} + \mathcal{O}(n^{-\ell-1-s}) \quad \text{as } n \rightarrow \infty, \text{ for some } \alpha_j \in \mathbb{R} \text{ with } \alpha_0 \neq 0, \quad (\text{A1.4}')$$

the discrete p -Hardy weight $\rho(\mathbf{g})$ of order ℓ is critical if $s \in [1/p, 1)$, non-attainable if $s \in (0, 1/p]$, and optimal near infinity if $s = 1/p$. Since the proof follows almost verbatim the arguments in Section 1.2.1.4, it will be omitted; see also [43, Theorem 3] for an analogous result in the linear case $p = 2$.

The final piece of the puzzle is to construct an explicit parameter sequence $\mathbf{g} \in H^\ell$ that fulfills all the assumptions (A1.1)–(A1.4). To this end, in Section 1.3, we shall examine the following candidate sequences:

- First, we consider a parameter sequence constructed in the form of a suitable Gamma function ratio:

$$\mathbf{g}_n^{(\ell,p)} := \frac{\Gamma(n + 1/q)}{\Gamma(n - \ell + 1)} \quad \text{for all } n \in \mathbb{Z}, \quad (1.18)$$

where Γ is the *Euler Gamma function*, and we consider $1/\Gamma$ to be an entire function with zeros at the points $0, -1, \dots$. In Section 1.3.1, we show that $\mathbf{g}^{(\ell,p)}$ gives rise to an optimal p -Hardy weight of order ℓ .

In particular, for $\ell = 1$, we discover the optimal first-order p -Hardy weight

$$\rho_n^{(1,p)} := \left(\frac{p-1}{p} \right)^{p-1} \left[\frac{1}{(n-1/p)^{p-1}} - \frac{1}{n^{p-1}} \right] \quad \text{for all } n \geq 1,$$

while in the linear case $p = 2$, we obtain the optimal Hardy weights of order ℓ in the form

$$\rho_n^{(\ell,2)} := \left(\frac{1}{2} \right)_\ell^2 \frac{1}{n(n-1/2)(n-1) \cdots (n-\ell+1/2)} \quad \text{for all } n \geq \ell.$$

These results complement the earlier works [17, 43], in which the optimal Hardy inequalities with the weights ρ^{FKP} and ρ_ℓ^{SW} , given by formulas (8) and (10), respectively, were established, and yield new weight sequences of a simpler and more explicit form. On the other hand, prior to this thesis, no (optimal) discrete p -Hardy weights of order $\ell \geq 2$ had been identified.

- Second, in light of the choice of $\mathbf{g}$ for $p = 2$ in (10), as well as the first-order p -Hardy weight (8) introduced by Fisher–Keller–Pogorzelski [17], it is natural to investigate also the following extension:

$$\tilde{\mathbf{g}}_n^{(\ell,p)} := n^{1-1/p} \prod_{j=1}^{\ell-1} (n-j) \quad \text{for all } n \geq 0 \quad \text{and} \quad \tilde{\mathbf{g}}_n^{(\ell,p)} := 0 \quad \text{for all } n < 0. \quad (1.19)$$

Even though it is fairly easy to verify assumptions (A1.1) and (A1.4) for the sequence (1.19), the nonlinearity of the discrete p -Laplace operator $-\Delta_p^{(k)}$ of order $k \in \mathbb{N}$ makes validating assumptions (A1.2) and (A1.3) a very non-trivial problem. Regrettably, we were unable to verify these assumptions in a general setting given by a combination of $p > 1$ and $\ell \in \mathbb{N}$. Partial results are summarized in Section 1.3.2.

1.2.1 Proofs

In this section, we systematically derive the proofs of Theorems 1.3, 1.7, 1.9, and 1.10.

1.2.1.1 Proof of Theorem 1.3

The proof of the inequalities in (1.12) relies on the following lemma, which provides auxiliary fundamental estimates and extends [14, Lemma 3.8] to the complex domain.

Lemma 1.13. *Let $t \in [0, 1]$. Then for any complex number $z \in \mathbb{C}$, we have the inequalities*

$$t|z-1|^2 (|z-t|+1-t)^{p-2} \lesssim |z-t|^p - (1-t)^{p-1}(|z|^p - t) \lesssim t^{p/2} |z-1|^p \quad \text{if } p \in (1, 2], \quad (1.20)$$

$$t|z-1|^2 (|z-t|+1-t)^{p-2} \gtrsim |z-t|^p - (1-t)^{p-1}(|z|^p - t) \gtrsim t^{p/2} |z-1|^p \quad \text{if } p \in (2, \infty). \quad (1.21)$$

(The left-hand side of (1.20) is to be understood as zero if $z = t = 1$.)

Proof (of Lemma 1.13). The proof is decomposed into two parts, in which we establish

- a) the lower bound for $p \in (1, 2]$, and, respectively, the upper bound for $p \in (2, \infty)$,
- b) the upper bound for $p \in (1, 2]$, and, respectively, the lower bound for $p \in (2, \infty)$,

for the term $|z - t|^p - (1 - t)^{p-1}(|z|^p - t)$. In both cases, the strategy is to extend the corresponding real-variable estimates, originally formulated in [14, Lemma 3.8], to the complex setting. However, the methods employed in a) and b) differ, which requires treating the two parts of the proof separately.

a) Suppose $p \in (1, 2]$. By [14, Lemma 3.8, Eq. (3.8)], there exists $C_p > 0$ sufficiently small, such that the inequality

$$C_p t |x - 1|^2 (|x - t| + 1 - t)^{p-2} \leq |x - t|^p - (1 - t)^{p-1}(|x|^p - t) \quad (1.22)$$

holds for all $t \in [0, 1]$ and $x \in \mathbb{R}$. For $z \in \mathbb{C}$, write $z = re^{i\theta}$, where $r = |z| \geq 0$ and $\theta \in [0, 2\pi)$ is the phase of z . Next, for $u := \cos \theta \in [-1, 1]$, denote

$$A(u) := |z - t| = \sqrt{r^2 - 2rtu + t^2} \quad \text{and} \quad B(u) := |z - 1| = \sqrt{r^2 - 2ru + 1}.$$

We will show that the auxiliary function

$$F(u) := A^p(u) - (1 - t)^{p-1}(r^p - t) - C_p t B^2(u)(A(u) + 1 - t)^{p-2},$$

defined on the interval $[-1, 1]$, is non-increasing, and hence attains its minimum at $u = 1$. Since $F(1) \geq 0$ by inequality (1.22), it follows that $F(u) \geq 0$ for all $u \in [-1, 1]$, which amounts to the lower estimate in (1.20). Indeed, a routine calculation yields

$$\begin{aligned} \frac{dF}{du} &= -prtA^{p-2} + C_p rt \left[2(A + 1 - t)^{p-2} + (p - 2)t \frac{B^2}{A} (A + 1 - t)^{p-3} \right] \\ &\leq rt [2C_p(A + 1 - t)^{p-2} - pA^{p-2}] \leq rtA^{p-2}(2C_p - p) \leq 0, \end{aligned} \quad (1.23)$$

for all $u \in (-1, 1)$ where we used the fact that $p \in (1, 2]$ twice and, without loss of generality, assumed that $C_p \leq p/2$.

The case $p \in (2, \infty)$ can be treated in an analogous manner. Observe that reverse inequalities in (1.22) and (1.23) hold for sufficiently large $C_p > 0$, therefore the auxiliary function F has a non-positive maximum at $u = 1$ and $F(u) \leq 0$ for all $u \in [-1, 1]$.

b) Suppose $p \in (1, 2]$. By [14, Lemma 3.8, Eq. (3.10)], there exists $C_p > 0$ sufficiently large, such that the inequality

$$|x - t|^p - (1 - t)^{p-1}(|x|^p - t) \leq C_p t^{p/2} |x - 1|^p \quad (1.24)$$

holds for all $t \in [0, 1]$ and $x \in \mathbb{R}$. We shall also make use of the elementary inequality [14, Lemma 3.8, Eq. (3.12)]

$$2^{s-1}(a^s + b^s) \leq (a + b)^s \leq a^s + b^s,$$

which is valid for all $a, b \geq 0$ and $s \in (0, 1]$. Denoting $z = re^{i\theta}$ and $u := \cos \theta$, from the latter inequalities with $s = p/2 \in (0, 1]$, we infer

$$|z - t|^2 = |r - t|^2 + 2rt(1 - u) \implies |z - t|^p \leq |r - t|^p + (2rt)^{p/2}(1 - u)^{p/2}, \quad (1.25)$$

$$|z - 1|^2 = |r - 1|^2 + 2r(1 - u) \implies |z - 1|^p \geq 2^{p/2-1} \left(|r - 1|^p + (2r)^{p/2}(1 - u)^{p/2} \right). \quad (1.26)$$

Without loss of generality, suppose additionally that $C_p \geq 1$. Then estimates (1.25), (1.24), and (1.26) imply

$$\begin{aligned} |z - t|^p - (1 - t)^{p-1}(|z|^p - t) &\leq |r - t|^p - (1 - t)^{p-1}(r^p - t) + (2rt)^{p/2}(1 - u)^{p/2} \\ &\leq C_p t^{p/2} \left(|r - 1|^p + (2r)^{p/2}(1 - u)^{p/2} \right) \leq 2^{1-p/2} C_p t^{p/2} |z - 1|^p. \end{aligned}$$

If $p \in (2, \infty)$, once more, all the inequalities (1.24), (1.25), and (1.26) are reversed, and the inverted final estimates hold, provided that $C_p > 0$ is chosen sufficiently small. The proof of Lemma 1.13 is complete. $\square$

We are now in a position to prove Theorem 1.3. Suppose $\mathbf{g} \in H^1$ is a non-decreasing sequence such that $\mathbf{g}_n > 0$ for all $n \geq 1$ and $u \in \mathcal{H}_0^1$. We will show that for all $n \geq 2$, we have the inequalities

$$\mathcal{R}(q; \mathbf{g}, u)_{n-1} \lesssim |\nabla u_n|^p - \left(\frac{|u_n|^p}{\mathbf{g}_n^{p-1}} - \frac{|u_{n-1}|^p}{\mathbf{g}_{n-1}^{p-1}} \right) (\nabla \mathbf{g}_n)^{p-1} \lesssim \mathcal{R}(p; \mathbf{g}, u)_{n-1}, \quad (1.27)$$

where the remainders are given by the formula (1.13) and the unspecified constant is independent of n . Next, consider $V_n \geq 0$ for all $n \geq 1$. Multiplying both sides of (1.27) by V_n and summing over n from 2 to ∞ , we arrive at

$$\sum_{n=2}^{\infty} V_n |\nabla u_n|^p + \sum_{n=1}^{\infty} V_{n+1} (\nabla \mathbf{g}_{n+1})^{p-1} \frac{|u_n|^p}{\mathbf{g}_n^{p-1}} - \sum_{n=2}^{\infty} V_n (\nabla \mathbf{g}_n)^{p-1} \frac{|u_n|^p}{\mathbf{g}_n^{p-1}} \left\{ \begin{array}{l} \gtrsim \sum_{n=2}^{\infty} V_n \mathcal{R}(q; \mathbf{g}, u)_{n-1}, \\ \lesssim \sum_{n=2}^{\infty} V_n \mathcal{R}(p; \mathbf{g}, u)_{n-1}. \end{array} \right.$$

Moreover, a shift of the index on the right-hand side reveals

$$\sum_{n=2}^{\infty} V_n |\nabla u_n|^p + \sum_{n=2}^{\infty} \frac{\operatorname{div}(V(\nabla \mathbf{g})^{p-1})_n}{\mathbf{g}_n^{p-1}} |u_n|^p + V_2 (\nabla \mathbf{g}_2)^{p-1} \frac{|u_1|^p}{\mathbf{g}_1^{p-1}} \left\{ \begin{array}{l} \gtrsim \sum_{n=1}^{\infty} V_{n+1} \mathcal{R}(q; \mathbf{g}, u)_n, \\ \lesssim \sum_{n=1}^{\infty} V_{n+1} \mathcal{R}(p; \mathbf{g}, u)_n. \end{array} \right.$$

Recalling $u_0 = \mathbf{g}_0 = 0$ and $\mathbf{g}_1 > 0$, we infer that

$$V_1 |\nabla u_1|^p = V_1 (\nabla \mathbf{g}_1)^{p-1} \frac{|u_1|^p}{\mathbf{g}_1^{p-1}}.$$

Adding and subtracting this term to the left-hand side of the latter inequality yields Theorem 1.3.

To complete the proof, it remains to verify the inequalities stated in (1.27). We shall confine our attention to the case $p \in (1, 2]$. The case $p \in (2, \infty)$ can be handled in a completely analogous fashion; the only modification required is the reversal of the inequalities in (1.20), (1.28), and (1.29). For $p \in (1, 2]$, inequalities (1.27) read

$$|\nabla u_n|^p - \left(\frac{|u_n|^p}{\mathbf{g}_n^{p-1}} - \frac{|u_{n-1}|^p}{\mathbf{g}_{n-1}^{p-1}} \right) (\nabla \mathbf{g}_n)^{p-1} \left\{ \begin{array}{l} \gtrsim \left| \sqrt{\frac{\mathbf{g}_{n-1}}{\mathbf{g}_n}} u_n - \sqrt{\frac{\mathbf{g}_n}{\mathbf{g}_{n-1}}} u_{n-1} \right|^2 \left(|\nabla u_n| + \frac{|u_{n-1}|}{\mathbf{g}_{n-1}} \nabla \mathbf{g}_n \right)^{p-2}, \\ \lesssim \left| \sqrt{\frac{\mathbf{g}_{n-1}}{\mathbf{g}_n}} u_n - \sqrt{\frac{\mathbf{g}_n}{\mathbf{g}_{n-1}}} u_{n-1} \right|^p. \end{array} \right. \quad (1.28)$$

We first consider the case $u_{n-1} = 0$. If in addition $u_n = 0$, then (1.28) holds trivially. If, on the other hand, $u_n \neq 0$, then (1.28) stems from the chain of inequalities

$$(p-1)t \leq 1 - (1-t)^{p-1} \leq t \leq t^{p/2}, \quad (1.29)$$

which are valid for every $t \in [0, 1]$, upon substituting $t = \mathbf{g}_{n-1}/\mathbf{g}_n \in (0, 1]$, where the latter inclusion is ensured by the monotonicity of $\mathbf{g}$ (note that the first inequality in (1.29) is an application of the Bernoulli inequality).

Next, assume $u_{n-1} \neq 0$ and temporarily set $h_n := u_n/\mathbf{g}_n$ and substitute for $z = h_n/h_{n-1} \in \mathbb{C}$ and $t = \mathbf{g}_{n-1}/\mathbf{g}_n \in (0, 1]$ into (1.20). It yields the inequalities

$$\begin{aligned} & \frac{\mathbf{g}_{n-1}}{\mathbf{g}_n} \left| \frac{h_n}{h_{n-1}} - 1 \right|^2 \left(\left| \frac{h_n}{h_{n-1}} - \frac{\mathbf{g}_{n-1}}{\mathbf{g}_n} \right| + 1 - \frac{\mathbf{g}_{n-1}}{\mathbf{g}_n} \right)^{p-2} \\ & \lesssim \left| \frac{h_n}{h_{n-1}} - \frac{\mathbf{g}_{n-1}}{\mathbf{g}_n} \right|^p - \left(1 - \frac{\mathbf{g}_{n-1}}{\mathbf{g}_n} \right)^{p-1} \left(\left| \frac{h_n}{h_{n-1}} \right|^p - \frac{\mathbf{g}_{n-1}}{\mathbf{g}_n} \right) \lesssim \left(\frac{\mathbf{g}_{n-1}}{\mathbf{g}_n} \right)^{p/2} \left| \frac{h_n}{h_{n-1}} - 1 \right|^p \end{aligned}$$

Finally, multiplying the latter inequalities by $\mathbf{g}_n^p |h_{n-1}|^p$ implies (1.28). The proof of Theorem 1.3 is complete. $\square$

1.2.1.2 Proof of Theorem 1.7

The proof proceeds by induction on $\ell \in \mathbb{N}$. The base case $\ell = 1$ is precisely Theorem 1.3 in the particular case $V \equiv 1$. Indeed, in view of definition (1.7) of the discrete gradient, assumption (A1.1) implies that $\mathbf{g} \in H^1$ defines a non-decreasing sequence; in fact, it is even increasing on $\{\ell - 1, \ell, \dots\}$.

Suppose $\ell \geq 2$. Recalling definitions of discrete gradient and divergence (1.7) and our convention, where $\operatorname{div} \nabla = \nabla \operatorname{div}$, specified in Section 1.1, we have

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p = \sum_{n=\ell-1}^{\infty} |\nabla^{\ell-1} \operatorname{div} u_n|^p \quad \text{for any } u \in \mathcal{H}_0^\ell.$$

Given $\mathbf{g} \in H^\ell$, such that assumptions (A1.1) and (A1.2) are fulfilled, we infer that $\operatorname{div} \mathbf{g} = S \nabla \mathbf{g} \in H^{\ell-1}$, where S is the forward shift operator (1.8), satisfies these assumptions for $\ell - 1$. The induction hypothesis, applied to $\operatorname{div} u \in \mathcal{H}_0^{\ell-1}$, with $\operatorname{div} \mathbf{g}$, yields

$$\sum_{k=1}^{\ell-1} R_k^{(\ell-1)}(q; \operatorname{div} \mathbf{g}, \operatorname{div} u) \lesssim \sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p - \sum_{n=\ell-1}^{\infty} \frac{-\Delta_p^{(\ell-1)} \operatorname{div} \mathbf{g}_n}{(\operatorname{div} \mathbf{g}_n)^{p-1}} |\operatorname{div} u_n|^p \lesssim \sum_{k=1}^{\ell-1} R_k^{(\ell-1)}(p; \operatorname{div} \mathbf{g}, \operatorname{div} u), \quad (1.30)$$

where the remainders are defined by formulas (1.17) and (1.13). Evidently, for all $k \in \{1, \dots, \ell - 1\}$ and $s > 1$, we have the identity

$$R_k^{(\ell-1)}(s; \operatorname{div} \mathbf{g}, \operatorname{div} u) = R_{k+1}^{(\ell)}(s; \mathbf{g}, u), \quad \text{thus} \quad \sum_{k=1}^{\ell-1} R_k^{(\ell-1)}(s; \operatorname{div} \mathbf{g}, \operatorname{div} u) = \sum_{k=2}^{\ell} R_k^{(\ell)}(s; \mathbf{g}, u).$$

Next, we shift the index n in the second sum of the middle part of the latter inequality, arriving at

$$\sum_{n=\ell-1}^{\infty} \frac{-\Delta_p^{(\ell-1)} \operatorname{div} \mathbf{g}_n}{(\operatorname{div} \mathbf{g}_n)^{p-1}} |\operatorname{div} u_n|^p = \sum_{n=1}^{\infty} \frac{S^{\ell-1}(-\Delta_p^{(\ell-1)} \nabla \mathbf{g})_n}{(S^{\ell-1} \nabla \mathbf{g}_n)^{p-1}} |\nabla S^{\ell-1} u_n|^p,$$

and we apply Theorem 1.3 with $S^{\ell-1} u \in \mathcal{H}_0^1$, non-decreasing sequence $S^{\ell-1} \mathbf{g} \in H^1$, and the weight

$$V_n := \frac{S^{\ell-1}(-\Delta_p^{(\ell-1)} \nabla \mathbf{g})_n}{(S^{\ell-1} \nabla \mathbf{g}_n)^{p-1}},$$

which is non-negative for all $n \geq 1$ by assumption (A1.2), obtaining

$$\sum_{n=1}^{\infty} V_n |\nabla S^{\ell-1} u_n|^p + \sum_{n=1}^{\infty} \frac{\operatorname{div}(V(\nabla S^{\ell-1} \mathbf{g})^{p-1})_n}{(S^{\ell-1} \nabla \mathbf{g}_n)^{p-1}} |S^{\ell-1} u_n|^p \begin{cases} \gtrsim \sum_{n=1}^{\infty} V_{n+1} \mathcal{R}(q; S^{\ell-1} \mathbf{g}, S^{\ell-1} u)_n, \\ \lesssim \sum_{n=1}^{\infty} V_{n+1} \mathcal{R}(p; S^{\ell-1} \mathbf{g}, S^{\ell-1} u)_n. \end{cases}$$

Let us examine the prefactor in the second sum in greater detail. We observe that

$$\operatorname{div}(V(\nabla S^{\ell-1} \mathbf{g})^{p-1}) = \operatorname{div} \left(\frac{S^{\ell-1}(-\Delta_p^{(\ell-1)} \nabla \mathbf{g})}{(S^{\ell-1} \nabla \mathbf{g})^{p-1}} (S^{\ell-1} \nabla \mathbf{g})^{p-1} \right) = -S^{\ell-1}(-\Delta_p^{(\ell)} \mathbf{g}).$$

Recalling also the definition of the remainders (1.17), the previous inequality rewrites as

$$R_1^{(\ell)}(q; \mathbf{g}, u) \lesssim \sum_{n=\ell-1}^{\infty} \frac{-\Delta_p^{(\ell-1)} \operatorname{div} \mathbf{g}_n}{(\operatorname{div} \mathbf{g}_n)^{p-1}} |\operatorname{div} u_n|^p - \sum_{n=\ell}^{\infty} \frac{-\Delta_p^{(\ell)} \mathbf{g}_n}{\mathbf{g}_n^{p-1}} |u_n|^p \lesssim R_1^{(\ell)}(p; \mathbf{g}, u). \quad (1.31)$$

Note that all the unspecified constants that define the estimates are the same and are determined by the fundamental inequalities (1.20), resp. (1.21).

Altogether, inequalities (1.30) and (1.31) combine to the desired estimate

$$\sum_{k=1}^{\ell} R_k^{(\ell)}(q; \mathbf{g}, u) \lesssim \sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p - \sum_{n=\ell}^{\infty} \frac{-\Delta_p^{(\ell)} \mathbf{g}_n}{\mathbf{g}_n^{p-1}} |u_n|^p \lesssim \sum_{k=1}^{\ell} R_k^{(\ell)}(p; \mathbf{g}, u),$$

which concludes the proof of Theorem 1.7. $\square$

1.2.1.3 Proof of Theorem 1.9

Recalling the definition of the remainders in (1.17), assumption (A1.2) guarantees their non-negativity. Furthermore, assumption (A1.3), i.e. the non-negativity of the sequence

$$\rho_n(\mathbf{g}) := -\Delta_p^{(\ell)} \mathbf{g}_n / \mathbf{g}_n^{p-1} \quad \text{for all } n \geq \ell,$$

combined with the lower bound provided by the abstract higher-order p -Hardy inequality (1.16) established in Theorem 1.7, implies that $\rho(\mathbf{g})$ is indeed a p -Hardy weight of order ℓ .

In order to prove the non-attainability in $\mathcal{H}_0^\ell$, suppose that $u \in \mathcal{H}_0^\ell$ fulfills the p -Birman inequality (1.10) as equality, that is

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p = \sum_{n=\ell}^{\infty} \rho_n(\mathbf{g}) |u_n|^p.$$

Since assumptions (A1.1) and (A1.2) are satisfied, Theorem 1.7 implies that all the remainder terms on the left-hand side of inequality (1.16) vanish, i.e. $R_k^{(\ell)}(q; \mathbf{g}, u) = 0$ for all $k \in \{1, \dots, \ell\}$. In particular, for $k = \ell$, we derive a necessary condition (which is, in fact, sufficient)

$$\mathcal{R}(q; \nabla^{\ell-1} \mathbf{g}, \nabla^{\ell-1} u)_n = 0 \quad \text{for all } n \geq \ell;$$

see definition (1.17). If $p \in (1, 2)$ (and hence $q \in (2, \infty)$), assumption (A1.1) implies in addition that both $\nabla^{\ell-1} \mathbf{g}_n$ and $\nabla^\ell \mathbf{g}_n$ are strictly positive for all $n \geq \ell$. Thus, the vanishing of the second factor in formula (1.13) yields $\nabla^{\ell-1} u_n = \nabla^{\ell-1} u_{n+1} = 0$. In any case, we conclude that the sequence $u \in \mathcal{H}_0^\ell$ satisfies the difference equation of order ℓ

$$\sqrt{\frac{\nabla^{\ell-1} \mathbf{g}_n}{\nabla^{\ell-1} \mathbf{g}_{n+1}}} \nabla^{\ell-1} u_{n+1} - \sqrt{\frac{\nabla^{\ell-1} \mathbf{g}_{n+1}}{\nabla^{\ell-1} \mathbf{g}_n}} \nabla^{\ell-1} u_n = 0 \quad \text{for all } n \geq \ell,$$

with the boundary conditions $u_1 = \dots = u_{\ell-1} = 0$.

However, this equation has the only solution $\mathbf{g}$ up to a multiplicative constant, i.e. $u_n = c \mathbf{g}_n$ for some constant $c \in \mathbb{C}$ and all $n \geq \ell$. By assumption (A1.1) for $k = 0$, $\mathbf{g}_n > 0$ for all $n \geq \ell$; therefore, the sequence u has compact support if and only if $c = 0$, or equivalently $u \equiv 0$. The proof of Theorem 1.9 is complete. $\square$

1.2.1.4 Proof of Theorem 1.10

The proof is organized into three distinct parts, in which we demonstrate that the weight $\rho(\mathbf{g}) = -\Delta_p^{(\ell)} \mathbf{g} / \mathbf{g}^{p-1}$ satisfies the properties required for a sequence to be optimal in the sense of Definition 1.1: criticality, non-attainability, and optimality near infinity. The proof is inspired by the linear case $p = 2$ in [43].

The key idea of the proof of non-attainability is that, for any $u \in \mathcal{H}_0^\ell$, equality in the p -Birman inequality entails that all the remainder terms appearing on the left-hand side of inequality (1.16) must vanish. On the other hand, the verification of criticality and optimality near infinity is obtained by substituting a suitable regularization of the parameter sequence $\mathbf{g}$ into inequality (1.16). Specifically, we apply inequality (1.16) to sequences $\{u^N\}_{N \geq 2} \subset \mathcal{H}_0^\ell$ and analyze the asymptotic behavior, as $N \rightarrow \infty$, of the remainder terms $R_k^{(\ell)}(p; \mathbf{g}, u^N)$ appearing on the right-hand side. To this end, we recall the following lemmas from [43]; the proofs can be found therein.

Lemma 1.14. *Let $k \in \mathbb{N}$, $\lambda \in \mathbb{R} \setminus \mathbb{N}_0$, and g be a sequence admitting the asymptotic expansion*

$$g_n = \sum_{j=0}^k a_j n^{\lambda-j} + \mathcal{O}(n^{\lambda-k-1}), \quad \text{as } n \rightarrow \infty, \quad (1.32)$$

for some $a_j \in \mathbb{R}$ and $a_0 \neq 0$. Then the following claims hold true:

(i) For all $m \in \mathbb{Z}$, there exist coefficients $a_j^{(m)} \in \mathbb{R}$ such that

$$S^m g_n = a_0 n^\lambda + \sum_{j=1}^k a_j^{(m)} n^{\lambda-j} + \mathcal{O}(n^{\lambda-k-1}), \quad \text{as } n \rightarrow \infty.$$

(ii) For all $m \in \mathbb{N}_0$, there exist coefficients $b_j^{(m)} \in \mathbb{R}$ with $b_0^{(m)} \neq 0$ such that

$$M^m g_n = \sum_{j=0}^k b_j^{(m)} n^{\lambda-j} + \mathcal{O}(n^{\lambda-k-1}), \quad \text{as } n \rightarrow \infty.$$

(iii) For all $m \in \{0, \dots, k\}$, there exist coefficients $c_j^{(m)} \in \mathbb{R}$ with $c_m^{(m)} \neq 0$ such that

$$\operatorname{div}^m g_n = \sum_{j=m}^k c_j^{(m)} n^{\lambda-j} + \mathcal{O}(n^{\lambda-k-1}), \quad \text{as } n \rightarrow \infty.$$

Claim (iii) of Lemma 1.14 asserts that the discrete derivative $\operatorname{div} \mathbf{g}$, for $\mathbf{g} \in C(\mathbb{Z})$ of the form (1.32), can be treated in a manner analogous to the continuous derivative $\mathbf{g}'$, once $\mathbf{g}$ is naturally extended to a function on $(0, \infty)$, as far as the asymptotic behavior is concerned. The following auxiliary claim, which generalizes the classical *Mean Value Theorem*, further elucidates the relationship between discrete and continuous derivatives.

Lemma 1.15. *Let $n \in \mathbb{Z}$, $m \in \mathbb{N}$, and $g \in C([n, n+m])$ such that $g \in C^m((n, n+m))$. Then there exists $\xi \in (n, n+m)$ such that*

$$\operatorname{div}^m g_n = g^{(m)}(\xi),$$

where we denoted $g_n := g(n)$.

Finally, we will make use of the *Leibniz formula* for the discrete divergence (1.7).

Lemma 1.16. *For all $m \in \mathbb{N}_0$ and sequences $f, g \in C(\mathbb{Z})$, we have*

$$\operatorname{div}^m(fg) = \sum_{j=0}^m \binom{m}{j} (\operatorname{div}^j M^{m-j} f) (\operatorname{div}^{m-j} M^j g),$$

where the multiplication of sequences is to be understood point-wise.

a) *Proof of criticality:* Suppose that $\tilde{\rho}$ is a p -Hardy weight of order ℓ such that $\tilde{\rho}_n \geq \rho_n(\mathbf{g})$ for all $n \geq \ell$. Employing the upper estimate in (1.16) for the weight $\rho(\mathbf{g})$ and the discrete p -Birman inequality (1.10) for the weight $\tilde{\rho}$, we find that

$$0 \leq \sum_{n=\ell}^{\infty} (\tilde{\rho}_n - \rho_n(\mathbf{g})) |u_n|^p \lesssim \sum_{k=1}^{\ell} R_k^{(\ell)}(p; \mathbf{g}, u) \quad (1.33)$$

for all sequences $u \in \mathcal{H}_0^\ell$.

A quick inspection of the remainders determined by formula (1.17) reveals that they are all simultaneously annihilated if we set $u = \mathbf{g}$, i.e. $R_k^{(\ell)}(p; \mathbf{g}, \mathbf{g}) \equiv 0$ for all $k \in \{1, \dots, \ell\}$ and $p > 1$. Unfortunately,

we cannot directly substitute $u = \mathbf{g}$ to (1.33) since $\mathbf{g} \notin \mathcal{H}_0^\ell$. To this end, we introduce the following regularization of $\mathbf{g}$. First, let us define a smooth cut-off function ξ^N , for any $N \geq 2$, as

$$\xi^N(x) := \begin{cases} 1 & \text{if } x \leq N, \\ \eta\left(\frac{2\log N - \log x}{\log N}\right) & \text{if } N < x \leq N^2, \\ 0 & \text{if } x > N^2, \end{cases} \quad (1.34)$$

where η is a smooth function, such that $\eta \equiv 0$ on $(-\infty, \varepsilon)$ and $\eta \equiv 1$ on $(1 - \varepsilon, \infty)$ for an arbitrary fixed $\varepsilon \in (0, 1/2)$. We set $u^N := \xi^N \mathbf{g}$ for all $N \geq 2$, where $\xi_n^N := \xi^N(n)$ for all $n \geq 1$.

Notice that by definition (1.34), we have $\xi^N \rightarrow 1$, and therefore $u^N \rightarrow \mathbf{g}$, point-wise as $N \rightarrow \infty$. We will show that this regularization admits the estimates

$$R_k^{(\ell)}(p; \mathbf{g}, u^N) \lesssim \frac{1}{\log^{p-1} N} \quad \text{if } p \in (1, 2] \quad \text{and} \quad R_k^{(\ell)}(p; \mathbf{g}, u^N) \lesssim \frac{1}{\log N} \quad \text{if } p \in (2, \infty) \quad (1.35)$$

for all $k \in \{1, \dots, \ell\}$. Here $\lesssim$ means inequality $\leq$ up to an N -independent constant, which may depend on k or p . Fatou's lemma, together with the inequality (1.33), then implies

$$\sum_{n=\ell}^{\infty} (\tilde{\rho}_n - \rho_n(\mathbf{g})) \mathbf{g}_n^p = \sum_{n=\ell}^{\infty} (\tilde{\rho}_n - \rho_n(\mathbf{g})) \lim_{N \rightarrow \infty} |u_n^N|^p \leq \liminf_{N \rightarrow \infty} \sum_{n=\ell}^{\infty} (\tilde{\rho}_n - \rho_n(\mathbf{g})) |u_n^N|^p = 0.$$

Bearing in mind that all the terms in the sum on the left are non-negative and $\mathbf{g}_n > 0$ for all $n \geq \ell$ by (A1.1), we may conclude that $\tilde{\rho}_n = \rho_n(\mathbf{g})$ for all $n \geq \ell$, which proves the criticality of the p -Birman weight $\rho(\mathbf{g})$.

It remains to establish the estimates (1.35), which will be carried out in the remainder of part a). Recall that the remainder terms are defined by formula (1.17). Upon replacing the gradient by the discrete divergence, we obtain

$$R_{k+1}^{(\ell)}(p; \mathbf{g}, u^N) = \sum_{n=\ell-k}^{\infty} \frac{-\Delta_p^{(\ell-k-1)} \operatorname{div}^{k+1} \mathbf{g}_n}{(\operatorname{div}^{k+1} \mathbf{g}_n)^{p-1}} \mathcal{R}(p; \operatorname{div}^k \mathbf{g}, \operatorname{div}^k u^N)_n$$

for all $k \in \{0, \dots, \ell - 1\}$, and we proceed to analyze the asymptotic behavior of the summands as $n \rightarrow \infty$, with $N \geq 2$ fixed.

We begin by deducing an upper bound of the first factor

$$\frac{-\Delta_p^{(\ell-k-1)} \operatorname{div}^{k+1} \mathbf{g}_n}{(\operatorname{div}^{k+1} \mathbf{g}_n)^{p-1}} \lesssim n^{p(k-\ell+1)} \quad (1.36)$$

for any $n \geq \ell - k$ and $k \in \{0, \dots, \ell - 1\}$, where the unspecified constant is n -independent. By assumption (A1.4) and claim (iii) of Lemma 1.14, we observe that

$$\operatorname{div}^m \mathbf{g}_n = c_0 n^{\ell-m-1/p} \left(1 + \sum_{j=m+1}^{2\ell} \frac{c_j}{c_0} n^{m-j} + \mathcal{O}(n^{m-2\ell-1}) \right), \quad \text{as } n \rightarrow \infty,$$

where $c_0 \neq 0$, for each $m \in \{0, \dots, 2\ell\}$. Furthermore, the generalized binomial theorem implies

$$(\operatorname{div}^m \mathbf{g}_n)^{p-1} = \sum_{j=0}^{2\ell-m} \tilde{c}_j n^{(p-1)(\ell-m-1/p)-j} + \mathcal{O}(n^{(p-1)(\ell-m-1/p)-2\ell+m-1}), \quad \text{as } n \rightarrow \infty, \quad (1.37)$$

where $\tilde{c}_0 \neq 0$. Using the shift operator (1.8) and the definition of the p -Laplacian (1.9), we may rewrite the numerator as

$$-\Delta_p^{(\ell-k-1)} \operatorname{div}^{k+1} \mathbf{g}_n = (-1)^{\ell+k+1} S^{k-\ell+1} \operatorname{div}^{\ell-k-1} (\operatorname{div}^\ell \mathbf{g}_n)^{p-1},$$

hence applying claims (i) and (iii) of Lemma 1.14 to the sequence $(\operatorname{div}^\ell \mathbf{g})^{p-1}$, we get

$$-\Delta_p^{(\ell-k-1)} \operatorname{div}^{k+1} \mathbf{g}_n \lesssim n^{k-\ell+1/p} \quad \text{and} \quad (\operatorname{div}^{k+1} \mathbf{g}_n)^{p-1} \asymp n^{(p-1)(\ell-k-1/p-1)}.$$

Inequality (1.36) follows immediately.

Next, we examine the asymptotic behavior of the second factor. Namely, we prove that

$$\mathcal{R}(p; \operatorname{div}^k \mathbf{g}, \operatorname{div}^k u^N)_n \lesssim \frac{n^{p(\ell-k-1/p-1)}}{\log^{\min\{p,2\}} N} \quad (1.38)$$

for all $p > 1$, where the unspecified constant does not depend on n nor N . First, we establish the inequality

$$\left| \sqrt{\frac{\operatorname{div}^k \mathbf{g}_n}{\operatorname{div}^k \mathbf{g}_{n+1}}} \operatorname{div}^k u_{n+1}^N - \sqrt{\frac{\operatorname{div}^k \mathbf{g}_{n+1}}{\operatorname{div}^k \mathbf{g}_n}} \operatorname{div}^k u_n^N \right| \lesssim \frac{n^{\ell-k-1/p-1}}{\log N} \quad (1.39)$$

for all $N \geq 2$, $n \geq \ell$, and $k \in \{0, \dots, \ell-1\}$. In fact, this result implicitly appeared in [43, Section 2.4], but for the sake of completeness, we will include the derivation of the inequality nonetheless. By assumption (A1.4) and claims (i) and (iii) of Lemma 1.14, we find that

$$\sqrt{\frac{\operatorname{div}^k \mathbf{g}_n}{\operatorname{div}^k \mathbf{g}_{n+1}}} \lesssim 1,$$

and therefore the left-hand side of (1.39) can be estimated as

$$\left| \sqrt{\frac{\operatorname{div}^k \mathbf{g}_n}{\operatorname{div}^k \mathbf{g}_{n+1}}} \operatorname{div}^k (\xi^N \mathbf{g})_{n+1} - \frac{\operatorname{div}^k \mathbf{g}_{n+1}}{\operatorname{div}^k \mathbf{g}_n} \operatorname{div}^k (\xi^N \mathbf{g})_n \right| \lesssim \left| \operatorname{div}^k (\xi^N \mathbf{g})_{n+1} - \frac{\operatorname{div}^k \mathbf{g}_{n+1}}{\operatorname{div}^k \mathbf{g}_n} \operatorname{div}^k (\xi^N \mathbf{g})_n \right|.$$

Invoking the Leibniz formula from Lemma 1.16, the last expression rewrites as

$$\begin{aligned} & \left| \sum_{j=0}^k \binom{k}{j} (\operatorname{div}^j \mathbf{M}^{k-j} \mathbf{g})_{n+1} (\operatorname{div}^{k-j} \mathbf{M}^j \xi^N)_{n+1} - \frac{\operatorname{div}^k \mathbf{g}_{n+1}}{\operatorname{div}^k \mathbf{g}_n} \sum_{j=0}^k \binom{k}{j} (\operatorname{div}^j \mathbf{M}^{k-j} \mathbf{g})_n (\operatorname{div}^{k-j} \mathbf{M}^j \xi^N)_n \right| \\ & \leq \sum_{j=0}^k \binom{k}{j} (\operatorname{div}^j \mathbf{M}^{k-j} \mathbf{g})_{n+1} \left| (\operatorname{div}^{k-j} \mathbf{M}^j \xi^N)_{n+1} - \frac{\operatorname{div}^k \mathbf{g}_{n+1}}{\operatorname{div}^k \mathbf{g}_n} \frac{\operatorname{div}^j \mathbf{M}^{k-j} \mathbf{g}_n}{\operatorname{div}^j \mathbf{M}^{k-j} \mathbf{g}_{n+1}} (\operatorname{div}^{k-j} \mathbf{M}^j \xi^N)_n \right|. \end{aligned}$$

Yet another application of (A1.4) and formulas from Lemma 1.14 reveals that

$$(\operatorname{div}^j \mathbf{M}^{k-j} \mathbf{g})_{n+1} \lesssim n^{\ell-j-1/p} \quad \text{and} \quad \frac{\operatorname{div}^k \mathbf{g}_{n+1}}{\operatorname{div}^k \mathbf{g}_n} \frac{\operatorname{div}^j \mathbf{M}^{k-j} \mathbf{g}_n}{\operatorname{div}^j \mathbf{M}^{k-j} \mathbf{g}_{n+1}} = \frac{1 + \mathcal{O}(1/n)}{1 + \mathcal{O}(1/n)} \frac{1 + \mathcal{O}(1/n)}{1 + \mathcal{O}(1/n)} = 1 + p_n^{(k,j)},$$

where $p_n^{(k,j)} = \mathcal{O}(1/n)$, as $n \rightarrow \infty$, i.e. $p_n^{(k,j)} \lesssim 1/n$, with $p^{(k,k)} \equiv 0$. Altogether, we deduce the upper bound of the left-hand side of (1.39) in the form

$$\sum_{j=0}^k \binom{k}{j} n^{\ell-j-1/p} \left(\left| (\operatorname{div}^{k-j+1} \mathbf{M}^j \xi^N)_{n+1} \right| + \left| p_n^{(k,j)} (\operatorname{div}^{k-j} \mathbf{M}^j \xi^N)_n \right| \right) \quad (1.40)$$

for all $N \geq 2$, $n \geq \ell$, and $k \in \{0, \dots, \ell - 1\}$. In order to obtain the desired estimate (1.39), we have to inspect also the asymptotic behavior of the terms with $\operatorname{div}^m \xi$ in (1.40). To this end, note that for all $x \in [N, N^2]$, we have

$$(\xi^N)'(x) = -\eta' \left(\frac{2 \log N - \log x}{\log N} \right) \frac{1}{x \log N},$$

thus $|(\xi^N)'(x)| \lesssim 1/(x \log N)$, where we estimated η' with $\max_{x \in [0, 1]} |\eta'(x)|$. It is straightforward to generalize this bound to higher-order derivatives, i.e.

$$|(\xi^N)^{(m)}(x)| \lesssim \frac{1}{x^m \log N}$$

for all $m \in \mathbb{N}$ and $x > 0$. Consequently, Lemma 1.15 implies that

$$|\operatorname{div}^m \xi_n^N| \lesssim \frac{1}{n^m \log N},$$

which is true for any $m, n \in \mathbb{N}$ and $N \geq 2$. By monotonicity of the right-hand side in the variable n , we also have

$$|\operatorname{div}^m M^j \xi_n^N| \lesssim \frac{1}{n^m \log N} \quad (1.41)$$

for any $j \in \mathbb{N}_0$, from which we infer a further upper estimate of (1.40)

$$\sum_{j=0}^{k-1} \binom{k}{j} n^{\ell-j-1/p} \left(\frac{1}{n^{k-j+1} \log N} + \frac{1}{n} \frac{1}{n^{k-j} \log N} \right) + n^{\ell-k-1/p} \frac{1}{n \log N} \lesssim \frac{n^{\ell-k-1/p-1}}{\log N},$$

finally arriving at (1.39).

If $p \in (1, 2]$, inequality (1.38) follows immediately from (1.39) and definition (1.13) of the corresponding remainders. If $p \in (2, \infty)$, we must also estimate the second factor in the defining formula (1.13). In particular, for all $k \in \{0, \dots, \ell - 1\}$, we show that

$$|\operatorname{div}^{k+1} u_n^N| + \frac{|\operatorname{div}^k u_n^N|}{\operatorname{div}^k \mathbf{g}_n} \operatorname{div}^{k+1} \mathbf{g}_n \lesssim n^{\ell-k-1/p-1} \quad \text{for all } n \geq \ell - k. \quad (1.42)$$

For any $k \in \{0, \dots, \ell\}$, Lemma 1.16 implies

$$\operatorname{div}^k u_n^N = \operatorname{div}^k (\xi^N \mathbf{g})_n = \sum_{j=0}^k \binom{k}{j} (\operatorname{div}^j M^{k-j} \mathbf{g})_n (\operatorname{div}^{k-j} M^j \xi^N)_n.$$

Using claims (ii) and (iii) of Lemma 1.14, together with the inequality (1.41), we infer that

$$(\operatorname{div}^j M^{k-j} \mathbf{g})_n \lesssim n^{\ell-j-1/p} \quad \text{and} \quad (\operatorname{div}^{k-j} M^j \xi^N)_n \lesssim n^{j-k}$$

for all $N \geq 2$, $n \geq \ell - k$, and $j \in \{0, \dots, k\}$. Note that the second estimate for $j = k$ follows from the obvious inequality $\xi^N \leq 1$. Altogether, we arrive at

$$\operatorname{div}^k u_n^N \lesssim n^{\ell-k-1/p}.$$

Moreover, employing claims (i) and (iii) of Lemma 1.14 once again, we find that

$$\frac{\operatorname{div}^{k+1} \mathbf{g}_n}{\operatorname{div}^k \mathbf{g}_n} \lesssim \frac{1}{n}.$$

Combining the above inequalities yields the estimate (1.42). Recalling definition (1.13), inequalities (1.39) and (1.42) amount to the desired inequality (1.38) for $p > 2$.

Finally, bearing inequalities (1.36) and (1.38) in mind, for all N sufficiently large, we obtain

$$\begin{aligned} R_{k+1}^{(\ell)}(p; \mathbf{g}, u^N) &= \sum_{n=N-k}^{N^2} \frac{-\Delta_p^{(\ell-1-k)} \operatorname{div}^{k+1} \mathbf{g}_n}{(\operatorname{div}^{k+1} \mathbf{g}_n)^{p-1}} \mathcal{R}(p; \operatorname{div}^k \mathbf{g}, \operatorname{div}^k u^N)_n \lesssim \frac{1}{\log^{\min\{p,2\}} N} \sum_{n=N-k}^{N^2} \frac{1}{n} \\ &\lesssim \frac{1}{\log^{\min\{p,2\}} N} \int_N^{N^2} \frac{1}{n} dn = \frac{1}{\log^{\min\{p,2\}-1} N} \end{aligned}$$

for all $k \in \{0, \dots, \ell-1\}$, which coincides with the aforementioned inequalities (1.35). The proof of criticality is complete.

b) *Proof of optimality near infinity*: Fix an arbitrary $M \geq \ell$. Recalling the definition of optimality near infinity (iii), (1.11), and inequality (1.16), we prove that the weight $\rho(\mathbf{g})$ enjoys this property by finding a sequence $\{u^N\}_{N \geq M} \subset \mathcal{H}_0^M$ such that

$$\lim_{N \rightarrow \infty} \frac{\sum_{k=1}^{\ell} R_k^{(\ell)}(p; \mathbf{g}, u^N)}{\sum_{n=\ell}^{\infty} \rho_n(\mathbf{g}) |u_n^N|^p} = 0. \quad (1.43)$$

Once again, the idea is to find a suitable regularization of the parameter sequence $\mathbf{g}$ so that it becomes an element of the space $\mathcal{H}_0^M$. In particular, we set $u^N := \xi^N \mathbf{g}$, where ξ is a smooth bump function determined by

$$\xi^N(x) := \begin{cases} 0 & \text{if } x \leq N, \\ \eta\left(\frac{\log x - \log N}{\log N}\right) & \text{if } N < x \leq N^2, \\ 1 & \text{if } N^2 < x \leq 2N^2, \\ \eta\left(\frac{\log(2N^3) - \log x}{\log N}\right) & \text{if } 2N^2 < x \leq 2N^3, \\ 0 & \text{if } x > 2N^3, \end{cases}$$

where the function η exhibits the same properties as in (1.34). Hence, indeed, $u^N \in \mathcal{H}_0^M$ for all $N \geq M$.

It is straightforward to show that inequality (1.41) still holds, i.e.

$$|M^j \xi_n^N| \lesssim 1 \quad \text{and} \quad |\operatorname{div}^m M^j \xi_n^N| \lesssim \frac{1}{n^m \log N}$$

for all $m, n \in \mathbb{N}$, $j \in \mathbb{N}_0$, and $N \geq M$. Therefore, the same arguments as in the proof of criticality a) apply, and we obtain the estimates (1.35) even with u^N defined above. Subsequently

$$R_{k+1}^{(\ell)}(p; \mathbf{g}, u^N) \lesssim \frac{1}{\log^{\min\{p,2\}} N} \left(\sum_{n=N-k}^{N^2} \frac{1}{n} + \sum_{n=2N^2-k}^{2N^3} \frac{1}{n} \right) \lesssim \frac{1}{\log^{\min\{p,2\}-1} N}$$

for all $k \in \{0, \dots, \ell-1\}$ and N sufficiently large, where the unspecified constant does not depend on N nor n , but may depend on p and k .

In order to finish the proof, we show that with our choice of u^N , the denominator in (1.43) is bounded from below by a positive constant. The above inequality then yields the desired limit. First, we inspect the asymptotic behavior of the weight $\rho_n(\mathbf{g}) = -\Delta_p^{(\ell)} \mathbf{g}_n / \mathbf{g}_n^{p-1}$ as $n \rightarrow \infty$. Recalling the definition (1.9) of the p -Laplacian, the numerator can be equivalently written as

$$-\Delta_p^{(\ell)} \mathbf{g}_n = (-1)^\ell S^{-\ell} \operatorname{div}^\ell (\operatorname{div}^\ell \mathbf{g}_n)^{p-1}.$$

Therefore, claims (i) and (iii) of Lemma 1.14, together with the expansion (1.37), imply

$$\rho_n(\mathbf{g}) \gtrsim \frac{n^{1/p-\ell-1}}{n^{(p-1)(\ell-1/p)}} = \frac{1}{n^{\ell p}} \quad (1.44)$$

for all $n \geq \ell$. Bearing (A1.4) in mind, we conclude that

$$\sum_{n=\ell}^{\infty} \rho_n(\mathfrak{g}) |u_n^N|^p \geq \sum_{n=N^2}^{2N^2} \rho_n(\mathfrak{g}) \mathfrak{g}_n^p \gtrsim \sum_{n=N^2}^{2N^2} \frac{n^{\ell p-1}}{n^{\ell p}} \geq \int_{N^2}^{2N^2} \frac{1}{n} dn = \log 2,$$

completing the proof of optimality near infinity.

c) *Proof of non-attainability:* Under the additional condition of strict positivity in assumption (A1.3), we first extend the lower bounds in (1.16) from $\mathcal{H}_0^\ell$, to the sequences in H^ℓ , for which equality is attained in the p -Birman inequality (1.10) and both sides are finite. To this end, we first formulate the following lemma, which asserts the density of the range of the operator ∇^ℓ in the space $\mathcal{H}^{\ell,p}$; see definition (1.6).

Lemma 1.17. *The range of the operator $\nabla^\ell|_{\mathcal{H}_0^\ell}$ is dense in $\mathcal{H}^{\ell,p}$.*

Proof (of Lemma 1.17). Recalling definition (1.7) of the discrete gradient, it is obvious that $\nabla^\ell(\mathcal{H}_0^\ell) \subset \mathcal{H}_0^\ell \subset \mathcal{H}^{\ell,p}$. By the Hahn-Banach Theorem, a subspace of a Banach space is dense if and only if its annihilator is trivial. Consequently the density of $\nabla^\ell(\mathcal{H}_0^\ell)$ in $\mathcal{H}^{\ell,p}$ will be established once we prove that if $v \in (\mathcal{H}^{\ell,p})^* \simeq \mathcal{H}^{\ell,q}$ satisfies

$$\langle v, \nabla^\ell u \rangle := \sum_{n=\ell}^{\infty} \overline{v_n} \nabla^\ell u_n = 0 \quad \text{for all } u \in \mathcal{H}_0^\ell, \quad (1.45)$$

then $v \equiv 0$. Moreover, up to the sign, the algebraic adjoint of the discrete gradient is divergence, i.e.

$$\langle v, \nabla u \rangle = \langle -\operatorname{div} v, u \rangle \quad \text{for all } v \in \mathcal{H}^{\ell,q} \text{ and } u \in \mathcal{H}^{\ell,p}.$$

Therefore, by taking $u = \delta_n$, that is $u_m = \delta_{nm}$, where δ is the Kronecker delta, for all $n \geq \ell$, in the condition (1.45), we observe that v solves the linear difference equation of order ℓ with constant coefficients

$$(-1)^\ell \operatorname{div}^\ell v_n = \sum_{j=0}^{\ell} \binom{\ell}{j} (-1)^j v_{n+j} = 0 \quad \text{for all } n \geq \ell.$$

It is straightforward to verify that the fundamental system of solutions for the above linear difference equation is given by the sequences $1, n, \dots, n^{\ell-1}$. Thus, we obtain

$$v_n = \sum_{j=0}^{\ell-1} c_j n^j \quad \text{for all } n \geq \ell$$

and some coefficients $c_j \in \mathbb{C}$. Furthermore, as $v \in \ell^q(\mathbb{Z})$, it follows that $c_j = 0$ for all $j \in \{0, \dots, \ell-1\}$. Combining this with the assumption $v \in H^\ell$, we conclude that $v \equiv 0$. The proof of Lemma 1.17 is complete. $\square$

Now suppose that $u \in H^\ell$ fulfills the p -Birman inequality (1.10) as equality whose (both) sides are finite, i.e.

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p = \sum_{n=\ell}^{\infty} \rho_n(\mathfrak{g}) |u_n|^p < \infty, \quad (1.46)$$

hence, specifically, $\nabla^\ell u \in \mathcal{H}^{\ell,p}$. By Lemma 1.17, there exists a sequence $\{u^N\}_{N=1}^\infty \subset \mathcal{H}_0^\ell$ such that $\nabla^\ell u^N \rightarrow \nabla^\ell u$ as $N \rightarrow \infty$ in the norm of $\ell^p(\mathbb{Z})$. In particular, the sequence is Cauchy in $\ell^p(\mathbb{Z})$.

Since assumptions (A1.1) and (A1.2) are satisfied, the Hardy inequality of order ℓ , valid on $\mathcal{H}_0^\ell$, with the weight $\rho(\mathfrak{g})$, which is non-negative by assumption (A1.3), implies

$$0 \leq \left\| \sqrt[p]{\rho(\mathfrak{g})} (u^N - u^M) \right\|_p \leq \left\| \nabla^\ell (u^N - u^M) \right\|_p \xrightarrow{N, M \rightarrow \infty} 0.$$

Consequently, the sequence $\{\sqrt[p]{\rho(\mathbf{g})} u^N\}_{N=1}^\infty$ is Cauchy and therefore convergent in $\ell^p(\mathbb{Z})$. Denote by v the ℓ^p -limit of $\sqrt[p]{\rho(\mathbf{g})} u^N$ as $N \rightarrow \infty$. It is immediate that $v \in \mathcal{H}^{\ell,p}$ and that, for every $n \in \mathbb{Z}$, we have $\sqrt[p]{\rho_n(\mathbf{g})} u_n^N \rightarrow v_n$ as $N \rightarrow \infty$. Since $\rho_n(\mathbf{g}) > 0$ for all $n \geq \ell$ by the strict inequalities in assumption (A1.3), there exists $\tilde{u} \in H^\ell$ such that $v = \sqrt[p]{\rho(\mathbf{g})} \tilde{u}$, and, in addition, $u_n^N \rightarrow \tilde{u}_n$ as $N \rightarrow \infty$ for all $n \in \mathbb{Z}$.

Moreover, the limits of all the above-mentioned ℓ^p -convergent sequences must coincide with their point-wise limits, i.e.

$$\nabla^\ell u^N \rightarrow \nabla^\ell \tilde{u} \quad \text{and} \quad \sqrt[p]{\rho(\mathbf{g})} u^N \rightarrow \sqrt[p]{\rho(\mathbf{g})} \tilde{u}$$

in $\ell^p(\mathbb{Z})$ as $N \rightarrow \infty$. In particular, we have $\nabla^\ell u = \nabla^\ell \tilde{u}$. This, however, implies $u = \tilde{u}$, because the linear operator ∇^ℓ is injective on H^ℓ . Indeed, if w solves the difference equation

$$\nabla^\ell w_n = 0 \quad \text{for all } n \geq \ell,$$

with the boundary condition $w_n = 0$ for all $n < \ell$, corresponding to the assumption $w \in H^\ell$, we recursively obtain $w_n = 0$ for all $n \in \mathbb{Z}$.

Therefore, recalling (1.46), tending $N \rightarrow \infty$ in the lower estimate in (1.16) for u^N , i.e. in

$$0 \leq \sum_{k=1}^{\ell} R_k^{(\ell)}(q; \mathbf{g}, u^N) \lesssim \sum_{n=\ell}^{\infty} |\nabla^\ell u_n^N|^p - \sum_{n=\ell}^{\infty} \rho_n(\mathbf{g}) |u_n^N|^p,$$

yields that the remainders on the left-hand side must vanish as $N \rightarrow \infty$. In view of definition (1.17), for $k = \ell$, Fatou's lemma entails

$$\lim_{N \rightarrow \infty} \mathcal{R}(q; \nabla^{\ell-1} \mathbf{g}, \nabla^{\ell-1} u^N)_n = \mathcal{R}(q; \nabla^{\ell-1} \mathbf{g}, \nabla^{\ell-1} u)_n = 0$$

for all $n \geq \ell$. Note that if $p \in (1, 2)$ (and hence $q \in (2, \infty)$), assumption (A1.1) implies in addition that both $\nabla^{\ell-1} \mathbf{g}_n$ and $\nabla^\ell \mathbf{g}_n$ are strictly positive for all $n \geq \ell$, hence the first identity remains valid even for $\nabla^{\ell-1} u_n = \nabla^{\ell-1} u_{n+1} = 0$ by inequality (1.28).

Similarly to the proof of Theorem 1.9 in Section 1.2.1.3, we find that $u_n = c \mathbf{g}_n$ for some constant $c \in \mathbb{C}$ and all $n \geq \ell$. From the estimate (1.44) and the asymptotic behavior of the parameter sequence $\mathbf{g}$, given by assumption (A1.4), we obtain

$$\rho_n(\mathbf{g}) \mathbf{g}_n^p \gtrsim \frac{1}{n^{\ell p}} n^{\ell p - 1} = \frac{1}{n} \quad \text{for all } n \geq \ell.$$

Finally, we conclude that

$$\sum_{n=\ell}^{\infty} \rho_n(\mathbf{g}) |u_n|^p \gtrsim \sum_{n=\ell}^{\infty} \frac{1}{n} = \infty,$$

whenever $c \neq 0$, thus, necessarily, $u \equiv 0$. The proof of non-attainability and therefore of Theorem 1.10 is complete. $\square$

1.3 Explicit optimal p -Birman weights

In this section, we implement the abstract framework introduced in Section 1.2 for the parameter sequences defined by formulas (1.18) and (1.19). Specifically, in view of Theorem 1.10, we focus on verifying assumptions (A1.1)–(A1.4), which will allow us to identify the weights

$$\rho_n^{(\ell,p)} := \frac{-\Delta_p^{(\ell)} \mathbf{g}_n^{(\ell,p)}}{(\mathbf{g}_n^{(\ell,p)})^{p-1}} \quad \text{and} \quad \tilde{\rho}_n^{(\ell,p)} := \frac{-\Delta_p^{(\ell)} \tilde{\mathbf{g}}_n^{(\ell,p)}}{(\tilde{\mathbf{g}}_n^{(\ell,p)})^{p-1}}, \quad (1.47)$$

defined for all $n \geq \ell$, as optimal p -Hardy weights of order ℓ .

The verification of assumptions (A1.1) and (A1.4) is straightforward. Assumption (A1.1) follows directly from the generalized Mean Value Theorem 1.15, while assumption (A1.4) is established using the known asymptotic expansions of the respective parameter sequences.

Conversely, the validation of assumptions (A1.2) and (A1.3) is substantially more involved, primarily due to the nonlinear nature of the p -Laplace operator (1.9). Under the assumption that (A1.1) holds for $k = \ell$, the joint validity of assumptions (A1.2) and (A1.3) is equivalently expressed as

$$(-1)^k \operatorname{div}^k (\operatorname{div}^\ell \mathbf{g}_n)^{p-1} \geq 0 \quad \text{for all } n > 0 \text{ and } k \in \{0, \dots, \ell\}, \quad (1.48)$$

which naturally leads to the notion of *completely monotone* functions.

Intermezzo: Completely monotone functions

A function $f : (0, \infty) \rightarrow \mathbb{R}$ is called *completely monotone* if and only if it is of the class C^∞ and it satisfies the *Bernstein–Hausdorff–Widder condition*

$$(-1)^k f^{(k)}(x) \geq 0 \quad \text{for all } k \geq 0 \text{ and } x > 0. \quad (1.49)$$

We denote the set of completely monotone functions as

$$\mathcal{CM} := \{f : (0, \infty) \rightarrow \mathbb{R} \mid f \text{ is completely monotone}\}.$$

The notion of completely monotone functions dates back to 1914 and S. Bernstein, who studied functions on $(-\infty, 0)$ with non-negative derivatives of all orders, i.e. functions satisfying (1.49) after omitting the alternating sign $(-1)^k$. Such functions are often called *absolutely monotone* in the literature. This, however, coincides with complete monotonicity up to a change of sign in the variable. Since then, the properties of completely monotone functions have been thoroughly studied, as they arise frequently in a wide range of mathematical disciplines, such as the moment problem, probability theory, and mathematical analysis. Here we discuss their surprising relevance also in the context of Hardy inequalities.

The often-cited book of D. V. Widder [40] contains a detailed account of properties of completely monotone functions. We point out Bernstein's theorem [40, Theorem 12a], which characterizes completely monotone functions as Laplace transforms of positive Borel measures. Namely, a function $f : (0, \infty) \rightarrow \mathbb{R}$ is completely monotone if and only if there exists a measure μ on $[0, \infty)$ such that

$$f(x) = \int_{[0, \infty)} e^{-xt} d\mu(t) \quad \text{for all } x > 0. \quad (1.50)$$

Remark 1.18. The Bernstein Theorem further implies that

$$(-1)^k f^{(k)}(x) = \int_{[0, \infty)} t^k e^{-xt} d\mu(t) \geq 0 \quad \text{for all } k \geq 0 \text{ and } x > 0,$$

which, in particular, shows that $f^{(k)}(x) \neq 0$ for all $k \geq 0$ and all $x > 0$, unless $f \in \mathcal{CM}$ is constant; see also [37, Remark 1.5]

Moreover, the aforementioned *Hausdorff moment problem* was studied therein. Analogously to the continuous case (1.49), a sequence $\{u_n\}_{n=0}^\infty \subset \mathbb{R}$ is called *completely monotone* if and only if

$$(-1)^k \operatorname{div}^k u_n \geq 0 \quad \text{for all } k \geq 0 \text{ and } n \geq 0.$$

We denote the set of completely monotone sequences on $\mathbb{N}_0$ as

$$\mathcal{CM}(\mathbb{N}_0) := \{u \in C(\mathbb{N}_0) \mid u \text{ is completely monotone}\}.$$

Hausdorff's Theorem [40, Theorem 4a] provides a necessary and sufficient condition for a sequence $\{u_n\}_{n \geq 0}$ to be completely monotone, that it admits the integral representation

$$u_n = \int_0^1 t^n d\mu(t) \quad \text{for all } n \geq 0, \quad (1.51)$$

for some finite Borel measure μ on the interval $[0, 1]$.

This formula also explains the connection between completely monotone functions and sequences. If $f \in \mathcal{CM}$ is right-continuous at 0, i.e. the limit of $f(x)$ as $x \rightarrow 0_+$ is finite, then $f_n := f(n)$ for all $n \geq 0$, where $f(0)$ is defined by the corresponding one-sided limit, defines a completely monotone sequence $f \in \mathcal{CM}(\mathbb{N}_0)$ by Lemma 1.15. On the other hand, if $u \in \mathcal{CM}(\mathbb{N}_0)$, one easily observes that

$$u(x) := \int_0^1 t^x d\mu(t), \quad \text{for all } x > 0,$$

where the measure μ is given by formula (1.51), defines a completely monotone function $u \in \mathcal{CM}$ continuous at 0. Consequently, this reduces many problems concerning completely monotone sequences to the more tractable continuous setting.

We now recall two classical properties of completely monotone functions. For the sake of completeness, we also include their short proofs. The first proposition asserts that the class $\mathcal{CM}$ is closed under multiplication.

Proposition 1.19. *If $f, g \in \mathcal{CM}$, then also $fg \in \mathcal{CM}$. Equivalently $\mathcal{CM} \cdot \mathcal{CM} \subset \mathcal{CM}$.*

Proof. The proof follows immediately from the Leibniz formula

$$(-1)^k (fg)^{(k)} = \sum_{j=0}^k \binom{k}{j} (-1)^j f^{(j)} (-1)^{k-j} g^{(k-j)}$$

for any $k \geq 0$ and definition (1.49). □

In view of the inequalities (1.48), we are particularly interested in determining whether the positive $(p-1)$ -st power of the functions $\text{div}^\ell \mathbf{g} \in \mathcal{CM}$ (see Lemmas 1.22 and 1.31) is itself completely monotone. However, a positive power of a completely monotone function is, in general, not completely monotone. This stability under positive powers is instead enjoyed by the class of *infinitely divisible* functions. A smooth function $f : (0, \infty) \rightarrow \mathbb{R}$ is called *infinitely divisible* if and only if

$$f^\lambda \in \mathcal{CM} \quad \text{for all } \lambda > 0.$$

We denote the set of infinitely divisible functions by $\mathcal{ID}$.

Infinitely divisible functions are closely related to another class, the *logarithmically completely monotone* functions. A smooth function $f : (0, \infty) \rightarrow (0, \infty)$ is said to be *logarithmically completely monotone* if and only if

$$-(\log f)' \in \mathcal{CM}. \quad (1.52)$$

We denote the set of logarithmically completely monotone functions by $\mathcal{LCM}$.

Proposition 1.20. *A logarithmically completely monotone function is infinitely divisible, and hence completely monotone. Equivalently $\mathcal{LCM} \subset \mathcal{ID} \subset \mathcal{CM}$.*

Proof. Obviously, if $f : (0, \infty) \rightarrow (0, \infty)$ is logarithmically completely monotone, then so is the function f^λ for any $\lambda > 0$. Consequently, it suffices to establish the inclusion $\mathcal{LCM} \subset \mathcal{CM}$.

Let $f \in \mathcal{LCM}$ and define a function $g : (-\infty, 0) \rightarrow (0, \infty) : x \mapsto f(-x)$. Observe that the function f is completely monotone if and only if g is absolutely monotone on $(b, 0)$ for all $b < 0$, i.e.

$$g^{(k)}(x) \geq 0 \quad \text{for all } k \geq 0 \text{ and } x \in (b, 0).$$

Fix arbitrary $b < 0$. By definition (1.52) and the Bernstein–Hausdorff–Widder condition (1.49), the function $(b, 0) \rightarrow (0, \infty) : x \mapsto (\log g(x))' = -(\log f)'(-x)$ is absolutely monotone on $(b, 0)$. Therefore, $\log g : (b, 0) \rightarrow \mathbb{R}$ is a non-decreasing function with a finite limit at the point b , thus there exist a constant $C \in \mathbb{R}$, such that $C + \log g : (b, 0) \rightarrow (0, \infty)$ is absolutely monotone on $(b, 0)$. Finally, we deduce that

$$g(x) = e^{-C} e^{C + \log g(x)}$$

is absolutely monotone on $(b, 0)$ as a constant multiple of a composition of absolutely monotone functions $x \mapsto e^x$ and $x \mapsto C + \log g(x)$. The proof of Proposition 1.20 is complete. $\square$

Remark 1.21. In fact, an even stronger connection between infinitely divisible and logarithmically completely monotone functions was established, for instance, in [37, Theorem 5.9]: a positive function $f : (0, \infty) \rightarrow (0, \infty)$ is infinitely divisible if and only if it is logarithmically completely monotone.

1.3.1 Parameter sequence as a ratio of Gamma functions

Recalling definition (1.18), we study the properties of the sequence

$$\mathbf{g}_n^{(\ell, p)} = \frac{\Gamma(n + 1/q)}{\Gamma(n - \ell + 1)} \quad \text{for all } n \in \mathbb{Z}. \quad (1.53)$$

In particular, we verify that the assumptions (A1.1)–(A1.4) are satisfied. Consequently, by Theorem 1.10, the sequence $\rho^{(\ell, p)}$, defined by formula (1.47), yields an optimal p -Hardy inequality of order ℓ .

Firstly, since the reciprocal Gamma function $1/\Gamma$ is an entire function on the complex plane with zeros at the points $0, -1, \dots$, it follows that $\mathbf{g}^{(\ell, p)} \in H^\ell$.

We now analyze the behavior of the sequence $\mathbf{g}^{(\ell, p)}$ under the action of the discrete divergence operator defined in (1.7). In particular, we uncover a full analog of the classical differentiation formula for monomials

$$\frac{d^k x^{\ell-1/p}}{dx^k} = (\ell - k + 1/q)_k x^{\ell-k-1/p}.$$

By extending the definition in (1.53) to all $\ell \in \mathbb{Z}$, we obtain the following result.

Lemma 1.22. *Let $\ell \in \mathbb{Z}$ and $k \in \mathbb{N}_0$. Then, for all $n \in \mathbb{Z}$, we have the identity*

$$\operatorname{div}^k \mathbf{g}_n^{(\ell, p)} = (\ell - k + 1/q)_k \mathbf{g}_n^{(\ell-k, p)}. \quad (1.54)$$

Proof. Bearing the operator identity $\operatorname{div} = S - I$ in mind, we obtain

$$\operatorname{div}^k \mathbf{g}_n^{(\ell, p)} = (-1)^k \sum_{j=0}^k \binom{k}{j} (-1)^j \frac{\Gamma(n + j + 1/q)}{\Gamma(n - \ell + j + 1)}$$

for all $n \in \mathbb{Z}$. Using the recurrence relation $\Gamma(z + 1) = z\Gamma(z)$, valid for all complex numbers $z \notin -\mathbb{N}_0$, we can further rewrite this expression in terms of the *regularized hypergeometric function* (see [13, Chapter 15]) as

$$\operatorname{div}^k \mathbf{g}_n^{(\ell, p)} = (-1)^k \Gamma(n + 1/q) \sum_{j=0}^k \frac{(-k)_j (n + 1/q)_j}{\Gamma(n - \ell + 1 + j) j!} \frac{1}{j!} = (-1)^k \Gamma(n + 1/q) {}_2F_1 \left(\begin{matrix} -k, n + 1/q \\ n - \ell + 1 \end{matrix} \middle| 1 \right).$$

Moreover, since $k \in \mathbb{N}_0$, the *Chu–Vandermonde identity* [13, Eq. (15.4.24)] implies

$${}_2F_1\left(\begin{matrix} -k, n+1/q \\ n-\ell+1 \end{matrix} \middle| 1\right) = \frac{(-\ell-1/q+1)_k}{\Gamma(n-\ell+k+1)},$$

hence, in view of the definition (1.53), we conclude that

$$\operatorname{div}^k \mathfrak{g}_n^{(\ell,p)} = (-1)^k (-\ell-1/q+1)_k \frac{\Gamma(n+1/q)}{\Gamma(n-\ell+k+1)} = (\ell-k+1/q)_k \mathfrak{g}_n^{(\ell-k,p)}$$

for all $n \in \mathbb{Z}$. $\square$

The explicit formula (1.54) plays a crucial role, as it yields a closed-form expression for the sequence $\operatorname{div}^\ell \mathfrak{g}^{(\ell,p)}$, thus significantly simplifying subsequent computations. This feature is the main motivation for working with the sequences $\mathfrak{g}^{(\ell,p)}$ rather than with $\tilde{\mathfrak{g}}^{(\ell,p)}$. Lemma 1.22, in turn, directly implies the following corollary.

Corollary 1.23. *Let $\ell \in \mathbb{N}$. Then the sequences $\mathfrak{g}^{(\ell,p)}$, defined by (1.53), satisfy the assumption (A1.1), i.e.*

$$\nabla^k \mathfrak{g}_n^{(\ell,p)} > 0 \quad \text{for all } n \geq \ell \text{ and } k \in \{0, \dots, \ell\}.$$

Proof. By definitions of the discrete gradient and divergence (1.7), Lemma 1.22 implies

$$\nabla^k \mathfrak{g}_n^{(\ell,p)} = (\ell-k+1/q)_k \mathfrak{g}_{n-k}^{(\ell-k,p)} > 0$$

for all $n \geq \ell \geq k \geq 0$. The strict positivity follows directly from the defining formula (1.53). $\square$

Moreover, the complete monotonicity of the sequence

$$\operatorname{div}^\ell \mathfrak{g}_n^{(\ell,p)} = \left(\frac{1}{q}\right)_\ell \frac{\Gamma(n+1/q)}{\Gamma(n+1)} \quad \text{for all } n \geq 0, \quad (1.55)$$

also follows directly from formula (1.54). In the subsequent proposition, we demonstrate that this sequence, in fact, satisfies even the stronger condition of logarithmic complete monotonicity (1.52). The assertion is a direct consequence of the more general result [2, Theorem 10]. Nevertheless, for the sake of completeness, we include a brief explanatory proof.

Proposition 1.24. *Let $q > 1$. Then the function*

$$G : (0, \infty) \rightarrow (0, \infty) : x \mapsto \frac{\Gamma(x+1/q)}{\Gamma(x+1)} \quad (1.56)$$

is logarithmically completely monotone.

Proof. Observe first that $G(x) > 0$ for all $x > 0$. We temporarily introduce the auxiliary function

$$H(x) := -(\log G(x))' = \psi(x+1) - \psi(x+1/q) \quad \text{for all } x > 0,$$

where ψ denotes the *digamma function*, which admits the integral representation [13, Eq. (5.9.16)]

$$\psi(x) := \frac{\Gamma'(x)}{\Gamma(x)} = -\gamma + \int_0^\infty \frac{e^{-t} - e^{-xt}}{1 - e^{-t}} dt \quad \text{for all } x > 0, \quad (1.57)$$

and $\gamma \in \mathbb{R}$ denotes the *Euler–Mascheroni constant*. Substituting this representation into the definition of H yields

$$H(x) = \int_0^\infty e^{-xt} \frac{e^{-t/q} - e^{-t}}{1 - e^{-t}} dt,$$

so that H can be written as a Laplace transform of the form (1.50). Since $q > 1$, the density of the associated Borel measure $(e^{-t/q} - e^{-t})/(1 - e^{-t})$ is strictly positive for all $t > 0$. Consequently,

$$(-1)^k H^{(k)}(x) = \int_0^\infty e^{-xt} t^k \frac{e^{-t/q} - e^{-t}}{1 - e^{-t}} dt > 0$$

for all $k \in \mathbb{N}_0$ and all $x > 0$. It follows that $H \in \mathcal{CM}$, and therefore $G \in \mathcal{LCM}$. $\square$

Corollary 1.25. *The sequences $\mathbf{g}^{(\ell,p)}$, defined by (1.53), satisfy the assumptions (A1.2) and (A1.3). In fact, we have the strict inequalities*

$$(-1)^k \operatorname{div}^k (\operatorname{div}^\ell \mathbf{g}_n^{(\ell,p)})^{p-1} > 0 \quad \text{for all } n \geq 0 \text{ and } k \geq 0. \quad (1.58)$$

Proof. As a direct consequence of Propositions 1.24 and 1.20, the function G , defined in (1.56), belongs to the class $\mathcal{LCM}$, and hence to $\mathcal{ID}$. Recalling also the formula (1.55), the right-continuity of G in zero, together with the Mean Value Theorem 1.15 implies that, for any $\lambda > 0$, we have

$$(-1)^k \operatorname{div}^k (\operatorname{div}^\ell \mathbf{g}_n^{(\ell,p)})^\lambda > 0 \quad \text{for all } n \geq 0 \text{ and } k \geq 0,$$

where the strict inequality follows from Remark 1.18. In particular, the choice $\lambda = p-1 > 1$ reproduces inequalities (1.58), which, in turn, guarantee that the assumptions (A1.2) and (A1.3) are satisfied. $\square$

Finally, we recall the asymptotic expansion for the ratio of Gamma functions [13, § 5.11(iii)]:

$$\frac{\Gamma(x+a)}{\Gamma(x+b)} \sim x^{a-b} \sum_{k=0}^{\infty} \frac{G_k(a,b)}{x^k}, \quad \text{as } x \rightarrow \infty, \text{ for all } a, b \in \mathbb{R}, \quad (1.59)$$

where the coefficients $G_k(a,b)$ are explicitly determined in terms of *generalized Bernoulli polynomials* $B_k^{(\lambda)}$ [13, § 24.16(i)] as

$$G_k(a,b) := \binom{a-b}{k} B_k^{(a-b+1)}(a) \quad \text{for all } k \in \mathbb{N}_0,$$

in particular $G_0(a,b) = 1 \neq 0$.

Corollary 1.26. *The sequences $\mathbf{g}^{(\ell,p)}$, defined by (1.53), satisfy the assumption (A1.4). In particular, $\mathbf{g}^{(\ell,p)}$ admits the asymptotic expansion*

$$\mathbf{g}_n^{(\ell,p)} \sim n^{\ell-1/p} \sum_{k=0}^{\infty} \frac{G_k(1/q, 1-\ell)}{n^k}, \quad \text{as } n \rightarrow \infty.$$

In light of Theorem 1.10, the results established in this section collectively yield the following theorem, which we regard as the second main result of this thesis.

Theorem 1.27. *Let $\ell \in \mathbb{N}$ and $p > 1$. Then the sequence*

$$\rho_n^{(\ell,p)} = \frac{-\Delta_p^{(\ell)} \mathbf{g}_n^{(\ell,p)}}{(\mathbf{g}_n^{(\ell,p)})^{p-1}} = \left(\frac{p-1}{p} \right)_\ell \frac{1}{(n-\ell+1-1/p)_\ell^{p-1}} \sum_{j=0}^{\ell} \frac{(-\ell)_j (n-\ell+1-1/p)_j^{p-1}}{(n-\ell+1)_j^{p-1}} \frac{1}{j!}, \quad (1.60)$$

for all $n \geq \ell$, where $\mathbf{g}^{(\ell,p)}$ is given by (1.53), is an optimal discrete p -Hardy weight of order ℓ .

Remark 1.28. If $p \geq 2$ is an integer, the weight $\rho^{(\ell,p)}$ can be represented in terms of *generalized hypergeometric functions* [13, § 16] as

$$\rho_n^{(\ell,p)} = \left(\frac{p-1}{p}\right)_\ell^{p-1} \frac{1}{(n-\ell+1-1/p)_\ell^{p-1}} {}_pF_{p-1}\left(\begin{matrix} -\ell, n-\ell+1-\frac{1}{p}, \dots, n-\ell+1-\frac{1}{p} \\ n-\ell+1, \dots, n-\ell+1 \end{matrix} \middle| 1\right),$$

for all $n \geq \ell$. In particular, for $p = 2$, an application of Lemma 1.22 yields the further simplification

$$\rho_n^{(\ell,2)} = \left(\frac{1}{2}\right)_\ell^2 \frac{1}{n(n-1/2)(n-1)\cdots(n-\ell+1/2)} > \left(\frac{1}{2}\right)_\ell^2 \frac{1}{n^{2\ell}}, \quad (1.61)$$

for all $n \geq \ell$. Consequently, this provides an additional more explicit examples of optimal Birman weights in the linear case $p = 2$, thereby expanding the family of such weights constructed in [43, Section 3].

Remark 1.29. In view of Remark 1.12, we further observe that the parameter sequences

$$\mathfrak{g}_n^{(\ell,p)}(s) := \frac{\Gamma(n+s)}{\Gamma(n-\ell+1)}, \quad \text{for all } n \in \mathbb{Z},$$

generate discrete p -Hardy weights of order ℓ , given by

$$\rho_n^{(\ell,p)}(s) := \frac{-\Delta_p^{(\ell)} \mathfrak{g}_n^{(\ell,p)}(s)}{(\mathfrak{g}_n^{(\ell,p)}(s))^{p-1}} = (s)_\ell^{p-1} \frac{1}{(n-\ell+s)_\ell^{p-1}} \sum_{j=0}^{\ell} \frac{(-\ell)_j (n-\ell+s)_j^{p-1}}{(n-\ell+1)_j^{p-1}} \frac{1}{j!} \quad \text{for all } n \geq \ell,$$

which are critical if $s \in (0, 1/q]$, non-attainable if $s \in [1/q, 1)$, and optimal near infinity if $s = 1/q$.

1.3.2 Parameter sequence as a linear combination of monomials

Motivated by the specific choice of the parameter sequences in (10), as well as by the optimal first-order p -Hardy inequality (7), we also analyze our second candidate $\tilde{\mathfrak{g}}^{(\ell,p)}$ defined by (1.19).

For $n \in \mathbb{N}$ and $k \in \{0, \dots, n-1\}$, we denote by

$$s(n, k) := (-1)^{n+k} \sum_{1 \leq i_1 < \dots < i_{n-k} < n} i_1 i_2 \dots i_{n-k}$$

the (signed) Stirling numbers of the first kind (see [13, § 26.8]). By convention, we additionally set $s(n, n) := 1$ for all $n \in \mathbb{N}$. Using the combinatorial identity [13, Eq. (26.8.7)], we obtain

$$\tilde{\mathfrak{g}}_n^{(\ell,p)} = n^{1-1/p} \prod_{j=1}^{\ell-1} (n-j) = \sum_{j=1}^{\ell} s(\ell, j) n^{j-1/p} \quad (1.62)$$

for all $n \geq 0$.

It is evident that $\tilde{\mathfrak{g}}^{(\ell,p)} \in H^\ell$ automatically satisfies assumption (A1.4). We now proceed to verify assumption (A1.1).

Proposition 1.30. *The sequences $\tilde{\mathfrak{g}}^{(\ell,p)}$, defined by formula (1.62), satisfy the assumption (A1.1), i.e.*

$$\nabla^k \tilde{\mathfrak{g}}_n^{(\ell,p)} > 0 \quad \text{for all } n \geq \ell \text{ and } k \in \{0, \dots, \ell\}. \quad (1.63)$$

Proof. Notice that since $\tilde{\mathfrak{g}}^{(\ell,p)} \in H^\ell$ by (1.62), it suffices to show inequalities (1.63) for $k = \ell$. Indeed, by definition of discrete gradient (1.7), $\nabla^\ell \tilde{\mathfrak{g}}_n^{(\ell,p)} > 0$ for all $n \geq \ell$ means that the sequence $\nabla^{\ell-1} \tilde{\mathfrak{g}}^{(\ell,p)}$

is strictly increasing on $\{\ell - 1, \ell, \dots\}$. Since $\nabla^{\ell-1} \tilde{\mathbf{g}}^{(\ell,p)} \in H^\ell$, hence $\nabla^{\ell-1} \tilde{\mathbf{g}}_{\ell-1}^{(\ell,p)} = 0$, we conclude that $\nabla^{\ell-1} \tilde{\mathbf{g}}_n^{(\ell,p)} > 0$ for all $n \geq \ell$. Iteration of this argument yields (1.63) for all $k \in \{0, \dots, \ell\}$.

In order to finish the proof, we establish the inequality

$$\nabla^\ell \tilde{\mathbf{g}}_n^{(\ell,p)} > 0$$

for all $n \geq \ell$. The key idea is to examine the natural extension of the sequence $\tilde{\mathbf{g}}^{(\ell,p)}$ to all positive real numbers, defined by

$$\tilde{\mathbf{g}}^{(\ell,p)}(x) := x^{1-1/p} \prod_{j=1}^{\ell-1} (x-j), \quad (1.64)$$

and make use of Lemma 1.15, which implies that for any $n \geq \ell$ there exists $\xi \in (n-\ell, n)$ such that

$$\nabla^\ell \tilde{\mathbf{g}}_n^{(\ell,p)} = \frac{d^\ell \tilde{\mathbf{g}}^{(\ell,p)}}{dx^\ell}(\xi).$$

Furthermore, bearing (1.62) in mind, we have

$$\frac{d^\ell \tilde{\mathbf{g}}^{(\ell,p)}}{dx^\ell}(x) = \sum_{j=1}^{\ell} s(\ell, j) \frac{d^\ell}{dx^\ell} x^{j-1/p} = \sum_{j=1}^{\ell} b_j^{(\ell,p)} x^{j-\ell-1/p} \quad (1.65)$$

for any $x > 0$, where

$$b_j^{(\ell,p)} := (-1)^{\ell+j} s(\ell, j) \prod_{k=0}^{\ell-1} |j-k-1/p| > 0$$

for all $j \in \{1, \dots, \ell\}$. The desired inequality follows immediately. $\square$

Recalling the operator formula $\text{div} = S - I$, we define the function

$$\tilde{G} : (0, \infty) \rightarrow \mathbb{R} : x \mapsto \text{div}^\ell \tilde{\mathbf{g}}^{(\ell,p)}(x) := \sum_{j=0}^{\ell} \binom{\ell}{j} (-1)^{\ell+j} \tilde{\mathbf{g}}^{(\ell,p)}(x+j), \quad (1.66)$$

where $\tilde{\mathbf{g}}^{(\ell,p)}$ is given by (1.64). Observing that higher-order derivatives of the function $\tilde{\mathbf{g}}^{(\ell,p)}$ in (1.65) begin to change sign, we arrive at the following lemma.

Lemma 1.31. *The function $\tilde{G} : (0, \infty) \rightarrow (0, \infty)$, defined by formula (1.66), is completely monotone.*

Proof. Consider an arbitrary $k \in \mathbb{N}_0$. Evidently, for any $x > 0$, we have

$$(-1)^k \tilde{G}^{(k)}(x) = (-1)^k \frac{d^k}{dx^k} \text{div}^\ell \tilde{\mathbf{g}}^{(\ell,p)}(x) = (-1)^k \text{div}^\ell \frac{d^k}{dx^k} \tilde{\mathbf{g}}^{(\ell,p)}(x).$$

Therefore, by Lemma 1.15, we readily infer that there exists $\xi \in (x, x+\ell)$ such that

$$(-1)^k \tilde{G}^{(k)}(x) = (-1)^k \frac{d^{\ell+k} \tilde{\mathbf{g}}^{(\ell,p)}}{dx^{\ell+k}}(\xi).$$

Furthermore, recalling formula (1.62), we find that

$$(-1)^k \frac{d^{\ell+k} \tilde{\mathbf{g}}^{(\ell,p)}}{dx^{\ell+k}}(x) = (-1)^k \sum_{j=1}^{\ell} s(\ell, j) \frac{d^{\ell+k}}{dx^{\ell+k}} x^{j-1/p} = \sum_{j=1}^{\ell} c_j^{(\ell,p)} x^{j-\ell-k-1/p}$$

for any $x > 0$, where

$$c_j^{(\ell,p)} = (-1)^k (-1)^{\ell+j+k} s(\ell, j) \prod_{m=0}^{\ell+k-1} |j - m - 1/p| > 0$$

for all $j \in \{1, \dots, \ell\}$. Altogether, we conclude that

$$(-1)^k \tilde{G}^{(k)}(x) > 0 \quad \text{for all } k \geq 0 \text{ and } x > 0,$$

hence the function $\tilde{G}$ is completely monotone. $\square$

The generalized Mean Value Theorem 1.15 ensures that $\text{div}^\ell \tilde{\mathbf{g}}^{(\ell,p)} \in \mathcal{CM}(\mathbb{N}_0)$ as well, thus inequalities (1.48) are fulfilled if the exponent $p - 1$ is omitted, in fact

$$(-1)^k \text{div}^k \text{div}^\ell \tilde{\mathbf{g}}_n^{(\ell,p)} > 0 \quad \text{for all } n \geq 0 \text{ and } k \geq 0.$$

In contrast to the function $G \in \mathcal{LCM}$ defined in (1.56), we were unable to establish the logarithmic complete monotonicity of $\tilde{G}$, and consequently we could not derive the inequalities in (1.48) for arbitrary $p > 1$. Nevertheless, by imposing suitable restrictions on the admissible values of $\ell \in \mathbb{N}$ and $p > 1$, we can infer the following result from Lemma 1.31.

Proposition 1.32. *Assume that one of the following conditions is satisfied:*

- (i) $\ell \in \mathbb{N}$ and $p \geq 2$ is an integer,
- (ii) $\ell \in \{3, 4, 5, 6, 7\}$ and $p > 2$,
- (iii) $\ell = 1$ or $\ell = 2$ and $p > 1$.

Then the sequence $\tilde{\mathbf{g}}^{(\ell,p)}$, given by (1.62), satisfies the assumptions (A1.2) and (A1.3), i.e.

$$(-1)^k \text{div}^k (\text{div}^\ell \tilde{\mathbf{g}}_n^{(\ell,p)})^{p-1} \geq 0 \quad \text{for all } n \geq 0 \text{ and } k \in \{1, \dots, \ell\}.$$

Proof. The proof is carried out in three separate steps, each corresponding to the fulfillment of the conditions (i), (ii), and (iii), respectively.

a) *Let $\ell \in \mathbb{N}$ and $p \geq 2$ be an integer:* Recall that the set of completely monotone functions is closed under multiplication by Proposition 1.19. Consequently, from Lemma 1.31, we infer that $\tilde{G}^{p-1} \in \mathcal{CM}$ and, by Remark 1.18 and Lemma 1.15, also

$$(-1)^k \text{div}^k (\text{div}^\ell \tilde{\mathbf{g}}_n^{(\ell,p)})^{p-1} > 0 \quad \text{for all } n \geq 0 \text{ and } k \geq 0. \quad (1.67)$$

In particular the inequalities hold for all $k \in \{1, \dots, \ell\}$, which completes the proof of part a).

If $p > 1$ is non-integer, the validation of inequalities (1.48) is much more complicated. In contrast to part a) of this proof, the inequalities will only be established for $k \in \{0, \dots, \ell\}$, for which reason, we introduce the following notation (cf. [38]).

Let $N \in \mathbb{N}^* := \mathbb{N} \cup \{\infty\}$. A function $f : (0, \infty) \rightarrow \mathbb{R}$ is called *completely monotone of order N* if and only if it is of class C^N and

$$(-1)^k f^{(k)}(x) \geq 0 \quad \text{for all } k \in \{0, \dots, N\} \text{ and } x > 0.$$

The set of completely monotone functions of order N is denoted as $\mathcal{CM}^N$, in particular, we have $\mathcal{CM}^\infty = \mathcal{CM}$. Furthermore, we define the set of functions, whose positive power is completely monotone, as

$$\mathcal{CM}_\lambda^N := \{f : (0, \infty) \rightarrow [0, \infty) \mid f^\lambda \in \mathcal{CM}^N\}$$

for any $\lambda > 0$ and $N \in \mathbb{N}^*$. In particular, we have $\mathcal{CM}_1^N = \mathcal{CM}^N$ and we abbreviate the notation if $N = \infty$ as $\mathcal{CM}_\lambda := \mathcal{CM}_\lambda^\infty$.

Invoking Lemma 1.15 once more, we observe that in order to show (1.48), it suffices to establish that $\tilde{G} \in \mathcal{CM}_{p-1}^\ell$. To this end, we will make use of the following results from [38, Theorem 4] and [39].

Lemma 1.33. *The following inclusions hold true:*

(i) *For any $N \in \{0, \dots, 5\}$, we have $\mathcal{CM}_\kappa^N \subset \mathcal{CM}_\lambda^N$ if $0 < \kappa \leq \lambda$.*

(ii) *For any $N \in \{0, \dots, 7\}$, we have $\mathcal{CM} \subset \mathcal{CM}_\lambda^N$ if $\lambda > 1$.*

Remark 1.34. Furthermore, the authors show that both claims of Lemma 1.33 fail to hold for sufficiently large N , thus, the following strategy cannot be extended to all $\ell \in \mathbb{N}$.

b) *Let $\ell \in \{3, 4, 5, 6, 7\}$ and $p > 2$:* Let us recall that $\tilde{G} \in \mathcal{CM}$ by Lemma 1.31. Invoking claim (ii) of Lemma 1.33 with $\lambda = p - 1 > 1$, we observe that $\tilde{G} \in \mathcal{CM}_{p-1}^\ell$. The statement then stems from the generalized Mean Value Theorem 1.15.

c) *Let $\ell = 1$ or $\ell = 2$ and $p > 1$:* For $\ell = 1$, the inequality is obvious. In fact, one straightforwardly observes that $\tilde{\mathbf{g}}^{(\ell,p)}$ always satisfies (1.48) with strict inequalities for $k = 1$, i.e.

$$(\operatorname{div}^\ell \tilde{\mathbf{g}}_n^{(\ell,p)})^{p-1} > (\operatorname{div}^\ell \tilde{\mathbf{g}}_{n+1}^{(\ell,p)})^{p-1} \quad \text{for all } n \geq 0, \quad (1.68)$$

by Lemmas 1.31 and 1.15 and Remark 1.18. For $\ell = 2$, we shall make use of the following auxiliary statement. See [32, Theorem 7] for the proof.

Lemma 1.35. *Let $N \geq 1$. Then for any $f \in \mathcal{CM}^{N+1}$, the function $f^{1/N}$ is convex.*

Let us temporarily denote $H := \operatorname{div}^2 \tilde{\mathbf{g}}^{(2,p)}$. By Lemmas 1.31 and 1.35, we have

$$\left(H^{1/N}(x)\right)' = \frac{1}{N} H^{1/N-1}(x) H'(x) < 0 \quad \text{and} \quad \left(H^{1/N}(x)\right)'' \geq 0$$

for all $N \geq 1$ and $x > 0$, therefore $H \in \mathcal{CM}_{1/N}^2$. Employing also claim (i) of Lemma 1.33, we conclude that $H \in \mathcal{CM}_\lambda^2$ for any $\lambda > 0$, hence, in particular, $H \in \mathcal{CM}_{p-1}^2$. A quick application of Lemma 1.15 reveals the desired result once again. The proof of Proposition 1.32 is complete. $\square$

In view of Theorems 1.9, Propositions 1.30 and 1.32 together imply that the sequences $\tilde{\rho}^{(\ell,p)}$, defined by (1.47), constitute p -Hardy weights of order ℓ , which are non-attainable in $\mathcal{H}_0^\ell$, for all combinations of $\ell \in \mathbb{N}$ and $p > 1$ specified in (i), (ii), and (iii).

In fact, a multitude of numerical tests, with a suitable CAS such as Wolfram Mathematica, suggest that not only $\tilde{G} \in \mathcal{CM}$, but also $\tilde{G} \in \mathcal{LCM}$, indeed. Consequently, we expect the following conjecture to hold true.

Conjecture 1.36. *Let $\ell \in \mathbb{N}$ and $p > 1$. The sequence $\tilde{\rho}^{(\ell,p)}$, given by (1.47), i.e.*

$$\tilde{\rho}_n^{(\ell,p)} = \frac{-\Delta_p^{(\ell)} \tilde{\mathbf{g}}_n^{(\ell,p)}}{(\tilde{\mathbf{g}}_n^{(\ell,p)})^{p-1}}$$

for all $n \geq \ell$, where $\tilde{\mathbf{g}}^{(\ell,p)}$ is defined by (1.19), is an optimal discrete p -Hardy weight of order ℓ .

Remark 1.37. In the cases where $\ell = 1$ or $p \geq 2$ is an integer, the hypothesis is an immediate consequence of Theorem 1.10 and the strict inequalities (1.67) and (1.68). In particular, for $\ell = 1$, we extended the first-order p -Hardy inequality (7), originally derived by Fisher–Keller–Pogorzelski in [17], to complex-valued sequences and, in addition, we established that the weight $\rho^{\text{FKP}} = \tilde{\rho}^{(1,p)}$ is not only null-critical, but also optimal in the sense of Definition 1.1.

1.4 Classical p -Birman inequality

In this section, we derive a discrete analog of the classical p -Birman inequality (1.1) on the half-line. Specifically, we establish the following theorem, which we regard as the third main result of this thesis.

Theorem 1.38 (classical discrete p -Birman inequality). *Let $\ell \in \mathbb{N}$ and $p > 1$. Then the inequality*

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p \geq \left(\frac{p-1}{p} \right)_\ell^p \sum_{n=\ell}^{\infty} \frac{|u_n|^p}{n^{\ell p}} \quad (1.69)$$

holds for all $u \in \mathcal{H}_0^\ell$ and the constant appearing on the right-hand side is optimal.

Remark 1.39. Inequality (1.69) can be equivalently written in discrete integral form. By solving the difference equation $\nabla^\ell u_n = v_n$ for $n \geq \ell$, with the initial condition $u_n = 0$ for $n < \ell$, one finds

$$u_n = \sum_{\ell \leq k_1 \leq \dots \leq k_\ell \leq n} v_{k_1} = \sum_{j=\ell}^n \binom{n+\ell-1-j}{\ell-1} v_j$$

for $n \geq \ell$. Substituting into (1.69) yields the inequality

$$\sum_{n=\ell}^{\infty} |v_n|^p \geq \left(\frac{p-1}{p} \right)_\ell^p \sum_{n=\ell}^{\infty} \left| \frac{1}{n^\ell} \sum_{k=\ell}^n \binom{n+\ell-1-k}{\ell-1} v_k \right|^p \quad (1.70)$$

for any $v \in C_0(\mathbb{N})$. In fact, using Fatou's lemma, inequality (1.70) extends to all complex sequences v . After shifting the index, Theorem 1.38 states that the generalized discrete Hardy operator

$$H^{(\ell)} v_n := \frac{1}{(n+\ell-1)^\ell} \sum_{k=1}^n \binom{n+\ell-1-k}{\ell-1} v_k$$

is bounded on $\ell^p(\mathbb{N})$, for all $1 < p < \infty$, with the operator norm equal to $1/(1-1/p)_\ell$.

The classical discrete p -Birman inequality (1.69) will be determined using two distinct methodological approaches:

- First, we derive a lower bound for the optimal weights $\rho^{(\ell,p)}$, defined in (1.47), and demonstrate that these weights yield an improvement over the corresponding classical weights on the right-hand side of (1.69).
- Second, we establish a Copson-type inequality with power weights of the form n^σ . This inequality is then applied iteratively in order to obtain the classical higher-order p -Hardy inequalities.

Finally, in Section 1.4.3, we derive the continuous p -Birman inequality (1.1) from its discrete counterpart and establish the optimality of the p -Birman constant

$$B_p^{(\ell)} := \left(\frac{p-1}{p} \right)_\ell^p, \quad (1.71)$$

demonstrating that this value remains sharp also in the continuous setting. Sections 1.4.2 and 1.4.3 closely follow our recently published paper [44], which extends the framework of [24] to the general case $p > 1$.

1.4.1 Lower bound for the optimal weights $\rho^{(\ell,p)}$

By detailed analysis of the optimal p -Hardy weights of order ℓ

$$\rho_n^{(\ell,p)} = \frac{-\Delta_p^{(\ell)} \mathfrak{g}_n^{(\ell,p)}}{(\mathfrak{g}_n^{(\ell,p)})^{p-1}} = \left(\frac{1}{q}\right)_\ell^{p-1} \left[\frac{\Gamma(n-\ell+1)}{\Gamma(n+1/q)} \right]^{p-1} \sum_{j=0}^{\ell} (-1)^j \binom{\ell}{j} \left[\frac{\Gamma(n-\ell+j+1/q)}{\Gamma(n-\ell+j+1)} \right]^{p-1}, \quad (1.72)$$

we will prove our next principal result:

Theorem 1.40. *Let $\ell \in \mathbb{N}$ and $p > 1$. Then the sequence $\rho^{(\ell,p)}$, given by formula (1.72), satisfies the inequality*

$$\rho_n^{(\ell,p)} > \left(\frac{p-1}{p}\right)_\ell^p \frac{1}{n^{\ell p}} \quad \text{for all } n \geq \ell.$$

Proof. The proof will be carried out separately for the cases $\ell = 1$ and $\ell \geq 2$, because Lemma 1.42, which plays a pivotal role in the latter case, does not remain valid in the regime $\ell = 1$.

a) *The case $\ell = 1$:* Since for $\ell = 1$ the weight $\rho^{(1,p)}$ assumes a relatively simple form, we establish an even stronger result: namely, that this weight admits a convergent series expansion in negative powers of n with all coefficients strictly positive, and with the leading coefficient coinciding with the classical p -Hardy constant. By formula (1.60), we have

$$\rho_n^{(1,p)} = \left(\frac{1}{q}\right)^{p-1} \left[\frac{1}{(n-1/p)^{p-1}} - \frac{1}{n^{p-1}} \right] = \left(\frac{1}{q}\right)^{p-1} n^{1-p} \left[\left(1 - \frac{1}{pn}\right)^{1-p} - 1 \right]$$

for all $n \geq 1$. Moreover, the generalized binomial theorem yields the series representation

$$\left(1 - \frac{1}{pn}\right)^{1-p} - 1 = \sum_{k=1}^{\infty} \binom{1-p}{k} \frac{(-1)^k}{p^k} \frac{1}{n^k},$$

which is valid for any $n \geq 1$, given that $p > 1$. Taking also into account the elementary identity

$$\binom{1-p}{k+1} (-1)^{k+1} = \frac{(p-1)(p)_k}{(k+1)!} \quad \text{for all } k \geq 0,$$

after shifting the index k , we finally obtain

$$\rho_n^{(1,p)} = \left(\frac{p-1}{p}\right)^p \sum_{k=0}^{\infty} \frac{(p)_k}{p^k} \frac{1}{(k+1)!} \frac{1}{n^{p+k}} > \left(\frac{p-1}{p}\right)^p \frac{1}{n^p} \quad (1.73)$$

for all $n \geq 1$.

b) *The case $\ell \geq 2$:* We now estimate the two factors appearing in (1.72) separately by means of the following two lemmas.

Lemma 1.41. *Let $\ell \in \mathbb{N}$ and $p > 1$. Then the inequality*

$$\frac{\Gamma(n-\ell+1)}{\Gamma(n+1/q)} > \frac{1}{n^\ell} n^{1/p}$$

holds for all $n \geq \ell$.

Proof (of Lemma 1.41). By using the recurrence relation $\Gamma(n+1) = n\Gamma(n)$, which holds for all $n \geq 1$, iteratively ℓ times, we obtain

$$\frac{\Gamma(n-\ell+1)}{\Gamma(n+1/q)} = \frac{1}{n(n-1)\cdots(n-\ell+1)} \frac{\Gamma(n+1)}{\Gamma(n+1/q)} \geq \frac{1}{n^\ell} \frac{\Gamma(n+1)}{\Gamma(n+1/q)}.$$

An application of the lower estimate in the Gautschi inequality [13, Eq. (5.6.4)]

$$x^{1-s} < \frac{\Gamma(x+1)}{\Gamma(x+s)} < (x+1)^{1-s} \quad \text{for all } x > 0 \text{ and } s \in (0, 1), \quad (1.74)$$

with $x = n \geq \ell > 0$ and $s = 1/q \in (0, 1)$, to the last term, yields the claim of Lemma 1.41. $\square$

Lemma 1.42. *Let $\ell \geq 2$ and $p > 1$. Then the inequality*

$$\sum_{j=0}^{\ell} (-1)^j \binom{\ell}{j} \left[\frac{\Gamma(n - \ell + j + 1/q)}{\Gamma(n - \ell + j + 1)} \right]^{p-1} \geq \left(\frac{1}{q} \right)_{\ell} \frac{1}{n^{\ell+1/q}}$$

holds for all $n \geq \ell$.

Proof (of Lemma 1.42). The proof will be divided into two steps. First, we replace the ratio of Gamma functions on the left-hand side of the inequality with a more convenient power sequence. Second, we obtain a lower bound for this new sequence that coincides with the right-hand side of the inequality.

Step 1: We derive the inequality

$$\sum_{j=0}^{\ell} (-1)^j \binom{\ell}{j} \left[\frac{\Gamma(n - \ell + j + 1/q)}{\Gamma(n - \ell + j + 1)} \right]^{p-1} \geq \sum_{j=0}^{\ell} (-1)^j \binom{\ell}{j} \frac{1}{(n - \ell + j + 1)^{1/q}} \quad (1.75)$$

for all $n \geq \ell \geq 0$, or, equivalently

$$(-1)^{\ell} \operatorname{div}^{\ell} \left[\left(\frac{\Gamma(n + 1/q)}{\Gamma(n + 1)} \right)^{p-1} - \frac{1}{(n + 1)^{1/q}} \right] \geq 0 \quad \text{for all } \ell \geq 0 \text{ and } n \geq 0.$$

Recalling the definition of complete monotonicity (1.49), together with the generalized Mean Value Theorem 1.15, the latter inequalities will follow once we show that the function

$$F : (0, \infty) \rightarrow \mathbb{R} : x \mapsto \left(\frac{\Gamma(x + 1/q)}{\Gamma(x + 1)} \right)^{p-1} - \frac{1}{(x + 1)^{1/q}}$$

is completely monotone, which we do in the remainder of this step.

First, we demonstrate that the function

$$g : (0, \infty) \rightarrow (0, \infty) : x \mapsto (x + 1)^{1/p} \frac{\Gamma(x + 1/q)}{\Gamma(x + 1)}$$

is logarithmically completely monotone, refining the result of Proposition 1.24; see (1.52) for the corresponding definition. Observe that the function g is indeed strictly positive and temporarily denote the auxiliary function

$$h(x) = -(\log g(x))' = \psi(x + 1) - \psi(x + 1/q) - \frac{1}{p(x + 1)} \quad \text{for all } x > 0.$$

Invoking the integral representations (1.57) for the digamma function ψ and

$$\frac{1}{x + 1} = \int_0^{\infty} e^{-(x+1)t} dt \quad \text{for all } x > 0,$$

we write the function h as a Laplace transform (1.50) of the form

$$h(x) = \int_0^{\infty} e^{-xt} k(t) dt \quad \text{for all } x > 0, \quad \text{with} \quad k(t) := e^{-t} \left(\frac{e^{t/p} - 1}{1 - e^{-t}} - \frac{1}{p} \right) \quad \text{for all } t > 0.$$

Elementary computations reveal that the density k is strictly positive on the interval $(0, \infty)$, from which we infer $h \in \mathcal{CM}$, and therefore $g \in \mathcal{LCM}$.

From the Gautschi inequality (1.74), we additionally deduce that $g(x) > 1$ for all $x > 0$. Therefore, in view of Proposition 1.20, which asserts that logarithmically completely monotone functions are infinitely divisible, it follows that $g^{p-1} - 1 \in \mathcal{CM}$. Finally, multiplying this function by the completely monotone function $x \mapsto (x+1)^{-1/q}$, we conclude that $F \in \mathcal{CM}$ as well, by Proposition 1.19.

Step 2: We further estimate the right-hand side of (1.75) as

$$\sum_{j=0}^{\ell} (-1)^j \binom{\ell}{j} \frac{1}{(n-\ell+j+1)^{1/q}} \geq \left(\frac{1}{q}\right)_{\ell} \frac{1}{n^{\ell+1/q}} \quad (1.76)$$

for all $n \geq \ell \geq 2$ (note that the inequality fails for $\ell = 1$). To this end, we will make use of the integral formula

$$\int_0^{\infty} t^{\lambda-1} e^{-xt} dt = \frac{\Gamma(\lambda)}{x^{\lambda}}, \quad \text{valid for all } \lambda, x > 0, \quad (1.77)$$

and rewrite the left-hand side of the latter inequality as

$$\sum_{j=0}^{\ell} (-1)^j \binom{\ell}{j} \frac{1}{(n-\ell+j+1)^{1/q}} = \frac{1}{\Gamma(1/q)} \sum_{j=0}^{\ell} (-1)^j \binom{\ell}{j} \int_0^{\infty} t^{1/q-1} e^{-(n-\ell+j+1)t} dt.$$

Moreover, upon interchanging the order of summation and integration, an application of the binomial theorem reveals

$$\sum_{j=0}^{\ell} (-1)^j \binom{\ell}{j} \int_0^{\infty} t^{1/q-1} e^{-(n-\ell+j+1)t} dt = \int_0^{\infty} t^{1/q-1} (1 - e^{-t})^{\ell} e^{(\ell-1)t} e^{-nt} dt.$$

Next, we estimate the integrand

$$(1 - e^{-t})^{\ell} e^{(\ell-1)t} \geq t^{\ell}, \quad \text{or equivalently} \quad \left(\frac{e^t - 1}{t}\right)^{\ell} \geq e^t.$$

Since $(e^t - 1)/t \geq 1$ for all $t > 0$ and $\ell \geq 2$, it suffices to verify that

$$\left(\frac{e^t - 1}{t}\right)^2 \geq e^t,$$

which, after taking square roots, stems from the elementary inequality $\sinh(t/2) \geq t/2$ for all $t > 0$.

Subsequently, invoking the identity (1.77) once more, the above integral is bounded from below as

$$\int_0^{\infty} t^{1/q-1} (1 - e^{-t})^{\ell} e^{(\ell-1)t} e^{-nt} dt \geq \int_0^{\infty} t^{\ell+1/q-1} e^{-nt} dt = \frac{\Gamma(\ell+1/q)}{n^{\ell+1/q}},$$

which, in turn, implies the desired inequality

$$\sum_{j=0}^{\ell} (-1)^j \binom{\ell}{j} \frac{1}{(n-\ell+j+1)^{1/q}} \geq \frac{\Gamma(\ell+1/q)}{\Gamma(1/q)} \frac{1}{n^{\ell+1/q}} = \left(\frac{1}{q}\right)_{\ell} \frac{1}{n^{\ell+1/q}}$$

for all $n \geq \ell \geq 2$. Combining inequalities (1.75) and (1.76) concludes the proof of Lemma 1.42. $\square$

Finally, from Lemmas 1.41 and 1.42, we obtain the desired estimate

$$\rho_n^{(\ell,p)} > \left(\frac{1}{q}\right)_{\ell}^{p-1} \frac{1}{n^{(p-1)\ell}} n^{1/q} \left(\frac{1}{q}\right)_{\ell} \frac{1}{n^{\ell+1/q}} = \left(\frac{p-1}{p}\right)_{\ell}^p \frac{1}{n^{\ell p}}$$

for all $n \geq \ell$. The proof of part b), and therefore of Theorem 1.40 is complete. $\square$

As an immediate corollary, we are now able to prove Theorem 1.38.

Proof (of Theorem 1.38). Since, by Theorem 1.27, the sequences $\rho^{(\ell,p)}$ constitute (optimal) p -Hardy weights of order ℓ , Theorem 1.40 yields, in turn, the classical p -Birman inequality

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p \geq \sum_{n=\ell}^{\infty} \rho_n^{(\ell,p)} |u_n|^p \geq \left(\frac{p-1}{p} \right)_\ell^p \sum_{n=\ell}^{\infty} \frac{|u_n|^p}{n^{\ell p}}$$

for all $u \in \mathcal{H}_0^\ell$. Notice that this inequality is sharp for every nontrivial sequence $u \neq 0$. Moreover, it is straightforward to verify that

$$\rho_n^{(\ell,p)} \sim \left(\frac{p-1}{p} \right)_\ell^p \frac{1}{n^{\ell p}}, \quad \text{as } n \rightarrow \infty.$$

Therefore, the optimality near infinity of the weights $\rho^{(\ell,p)}$ implies the optimality of the p -Birman constant on the right-hand side. The proof of Theorem 1.38 is complete. $\square$

In [43], we investigated another remarkable property of the optimal Hardy weights ρ_ℓ^{SW} of order ℓ , defined in (10). In analogy with the expansion (1.73) of the weight $\rho^{(1,p)}$, we proved that $\rho_\ell^{\text{SW}}(n)$ admits a convergent series representation in negative powers of n , whose coefficients are all non-negative (and, in fact, strictly positive for $\ell \geq 2$) for every $n \geq \ell$. This representation is particularly useful, since including additional terms of the truncated series yields progressively tighter Birman inequalities with very explicit weights.

We observed the same behavior also for the optimal first-order p -Hardy weight $\rho^{\text{FKP}} = \tilde{\rho}^{(1,p)}$ introduced by Fisher, Keller, and Pogorzelski; see definitions (8) and (1.47). This phenomenon was originally conjectured in [17] and subsequently established in [42] abusing the theory of Herglotz–Nevanlinna functions. In contrast, the proof of the expansion (1.73) for the new weight $\rho^{(1,p)}$ is considerably more elementary.

For higher-order weights, the situation becomes substantially more intricate. Nevertheless, numerical experiments indicate that the following conjecture is valid. We will establish this conjecture in the cases $\ell = 1$ or $p = 2$.

Conjecture 1.43. *Let $\ell \in \mathbb{N}$ and $p > 1$. Then the sequence $\rho^{(\ell,p)}$, given by formula (1.60), admits a convergent series expansion*

$$\rho_n^{(\ell,p)} = \left(\frac{p-1}{p} \right)_\ell^p \sum_{k=0}^{\infty} \frac{A_k^{(\ell,p)}}{n^{\ell p + k}} \quad \text{for all } n \geq \ell,$$

with $A_k^{(\ell,p)} > 0$ for all $k \geq 0$ and $A_0^{(\ell,p)} = 1$.

Proof (for $\ell = 1$ or $p = 2$). For $\ell = 1$, the expansion is given by formula (1.73), with

$$A_k^{(1,p)} = \frac{(p)_k}{p^k} \frac{1}{(k+1)!} \quad \text{for all } k \geq 0.$$

On the other hand, in the special case $p = 2$, the weight $\rho^{(\ell,2)}$ reduces to the expression given in (1.61). Consequently, invoking the identity [13, Eq. (26.8.11)], we have

$$\rho_n^{(\ell,2)} = \left(\frac{1}{2} \right)_\ell^2 \sum_{k=0}^{\infty} \frac{S(2\ell-1+k, 2\ell-1)}{2^k} \frac{1}{n^{2\ell+k}}, \quad \text{i.e.} \quad A_k^{(\ell,2)} = \frac{S(2\ell-1+k, 2\ell-1)}{2^k},$$

for all $k \geq 0$, where

$$S(n, k) := \sum_{\substack{j_1, \dots, j_k \geq 0 \\ j_1 + \dots + j_k = n-k}} 1^{j_1} 2^{j_2} \dots k^{j_k}, \quad \text{for all } n \in \mathbb{N} \text{ and } k \in \{0, \dots, n-1\},$$

denote the *Stirling numbers of the second kind*, with the convention $S(n, n) = 1$ for all $n \in \mathbb{N}$. $\square$

1.4.2 The Copson inequality with negative exponents

Here, we prove the classical p -Birman inequality (1.69) by an iterative application of a weighted discrete p -Hardy inequality, similar to the classical *Copson inequality*

$$\sum_{n=1}^{\infty} n^{\sigma} |\nabla u_n|^p \geq \left(\frac{p - \sigma - 1}{p} \right)^p \sum_{n=1}^{\infty} n^{\sigma-p} |u_n|^p, \quad (1.78)$$

where $u \in \mathcal{H}_0^1$ and $0 \leq \sigma < p - 1$. The non-negativity of σ in (1.78) is essential, as the inequality fails for $\sigma < 0$, which is precisely the regime required for our proof of (1.69). If $\sigma < 0$, a slightly smaller weight is required on the right-hand side. We present this version of Copson inequality in the next theorem, as it may be of independent interest. Copson's original work [7] contains a proof of (1.78), while the optimality of the *Copson constant*

$$C_p^{(\sigma)} := \left(\frac{p - \sigma - 1}{p} \right)^p \quad (1.79)$$

is established, for example, in [3, Corollary 3].

Theorem 1.44. *Let $\sigma < 0$ and $p > 1$. Then the inequality*

$$\sum_{n=1}^{\infty} n^{\sigma} |\nabla u_n|^p \geq \left(\frac{p - \sigma - 1}{p} \right)^p \sum_{n=1}^{\infty} (n+1)^{\sigma-p} |u_n|^p, \quad (1.80)$$

holds for all $u \in \mathcal{H}_0^1$ and the constant appearing on the right-hand side is optimal.

Proof. We prove (1.80) by choosing V_n in Theorem 1.3 as a power sequence and $\mathfrak{g}_n$, once again, as a suitable Gamma ratio. In particular, we set

$$V_n := \begin{cases} 0 & \text{if } n = 1, \\ (n-1)^{\sigma} & \text{if } n \geq 2, \end{cases} \quad \mathfrak{g}_n := \begin{cases} 0 & \text{if } n \leq 0, \\ \Gamma(n+1 - \frac{\sigma+1}{p}) / \Gamma(n) & \text{if } n \geq 1. \end{cases} \quad (1.81)$$

Since for all $n \geq 2$, we have

$$\mathfrak{g}_n - \mathfrak{g}_{n-1} = \frac{p - \sigma - 1}{p} \frac{\Gamma(n - \frac{\sigma+1}{p})}{\Gamma(n)} > 0,$$

the sequence $\mathfrak{g}$ is increasing. As the other assumptions of Theorem 1.3 are fulfilled trivially, we obtain the inequality

$$\sum_{n=2}^{\infty} (n-1)^{\sigma} |\nabla u_n|^p \geq \sum_{n=2}^{\infty} \rho_n |u_n|^p$$

for all $u \in \mathcal{H}_0^2$ (here we additionally require that $u_1 = 0$), where

$$\rho_n := -\frac{\operatorname{div}(V(\nabla \mathfrak{g})^{p-1})_n}{(\mathfrak{g}_n)^{p-1}} = \left(\frac{p - \sigma - 1}{p} \right)^{p-1} n^{\sigma-p+1} H\left(\frac{1}{n}\right) \quad (1.82)$$

and H is an auxiliary function defined on the interval $[0, 1)$ by

$$H(x) := \frac{(1-x)^{\sigma}}{(1 - \frac{\sigma+1}{p}x)^{p-1}} - 1.$$

In order to establish the inequality (1.80), it suffices to show that H satisfies

$$H(x) > \frac{p - \sigma - 1}{p} x \quad \text{for all } x \in (0, 1). \quad (1.83)$$

Since $H(0) = 0$ and $H'(0) = (p - \sigma - 1)/p$, inequality (1.83) can be written as $H(x) > H(0) + H'(0)x$, and so it holds true if H is strictly convex on $(0, 1)$. A routine calculation yields

$$H''(x) = \frac{p - \sigma - 1}{p^2} \frac{(1 - x)^{\sigma-2}}{\left(1 - \frac{\sigma+1}{p}x\right)^{p+1}} \left[(p - \sigma)(1 + \sigma)^2 x^2 - 2(1 + \sigma)(p - \sigma)x + p(1 - \sigma)\right].$$

Since the discriminant $4\sigma(1 + \sigma)^2(p - 1)(p - \sigma)$ of the quadratic term is negative, we conclude that $H''(x) > 0$ for all $x \in (0, 1)$, indeed.

Furthermore, in complete analogy with the proof of Theorem 1.10 in Section 1.2.1.4, one can verify that the weight ρ , defined by (1.82), is optimal (the notion of optimality given in Definition 1.1 can be extended in a straightforward manner to the setting of weighted Hardy inequalities). In particular, ρ is optimal near infinity, and hence the optimality of the Copson constant (1.79) on the right-hand side of inequality (1.80) follows immediately from the asymptotics

$$\rho_n \sim \left(\frac{p - \sigma - 1}{p}\right)^p n^{\sigma-p}, \quad \text{as } n \rightarrow \infty.$$

The details are left as an exercise for the reader. See also Remark 1.50 for an alternative proof of the optimality of the Copson constant. The proof of Theorem 1.44 is complete. $\square$

Remark 1.45. The Copson inequality (1.78) can also be established using the approach described above. Assuming $0 \leq \sigma < p - 1$, we apply Theorem 1.3 with $V_n := n^\sigma$ and $\mathbf{g}_n$ defined in (1.81). This yields the inequality

$$\sum_{n=1}^{\infty} n^\sigma |\nabla u_n|^p \geq \sum_{n=1}^{\infty} \rho_n |u_n|^p, \quad (1.84)$$

with ρ_n given by (1.82), but with the function H redefined on $[0, 1]$ by

$$H(x) := \left(1 - \frac{\sigma + 1}{p}x\right)^{1-p} - (1 + x)^\sigma.$$

Although this version of H is no longer convex on $(0, 1)$, inequality (1.83) remains true and can be verified as follows. First, we observe that $H^{(\lceil \sigma \rceil + 1)}(x) > 0$ for all $x \in (0, 1)$. Noticing also that $H(0) = 0$ and $H'(0) = (p - \sigma - 1)/p$, the Taylor–Lagrange formula implies that, for any $x \in (0, 1)$, there exists $\xi \in (0, 1)$ such that

$$H(x) = \frac{p - \sigma - 1}{p}x + \sum_{k=2}^{\lceil \sigma \rceil} \frac{H^{(k)}(0)}{k!}x^k + \frac{H^{(\lceil \sigma \rceil + 1)}(\xi)}{(\lceil \sigma \rceil + 1)!}x^{\lceil \sigma \rceil + 1},$$

from which the desired inequality follows if $H^{(k)}(0) \geq 0$ for all $k \in \{2, \dots, \lceil \sigma \rceil\}$. To verify also the last claim and finish the proof, we estimate

$$\begin{aligned} H^{(k)}(0) &= \frac{(p + k - 2)(p + k - 3) \cdots (p - 1)}{p^k} (\sigma + 1)^k - \sigma(\sigma - 1) \cdots (\sigma - k + 1) \\ &\geq \left(1 - \frac{1}{p}\right) (\sigma + 1)^k - \sigma^k \geq \left(1 - \frac{1}{\sigma + 1}\right) (\sigma + 1)^k - \sigma^k = \sigma(\sigma + 1)^{k-1} - \sigma^k \geq 0. \end{aligned}$$

Furthermore, inequality (1.84), once again, offers an optimal version of the Copson inequality, which can be of independent interest, as the existing literature on such refinements, for example [8, 9, 10], seems to consider only the special case $p = 2$.

Proof (of Theorem 1.38). Here, we restrict our attention to establishing the inequality (1.69). An alternative proof of the optimality of the p -Birman constant $B_p^{(\ell)}$, distinct from the argument developed in Section 1.4.1 and independent of the optimal weights obtained in Theorem 1.27, is provided in Remark 1.50.

The proof proceeds by induction on $\ell \in \mathbb{N}$. For the base case $\ell = 1$, inequality (1.69) coincides with the classical p -Hardy inequality (1).

Assume $\ell \geq 2$ and pick $u \in \mathcal{H}_0^\ell$. Recalling definitions of the discrete gradient and divergence (1.7), we have the identities $\operatorname{div} = \nabla S = S \nabla$ and $\operatorname{div} \nabla = \nabla \operatorname{div}$. It follows that

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p = \sum_{n=\ell-1}^{\infty} |\nabla^{\ell-1} \operatorname{div} u_n|^p \geq B_p^{(\ell-1)} \sum_{n=\ell-1}^{\infty} \frac{|\operatorname{div} u_n|^p}{n^{(\ell-1)p}},$$

where we applied the induction hypothesis on the sequence $\operatorname{div} u \in \mathcal{H}_0^{\ell-1}$. Using once more the identity $\operatorname{div} = \nabla S$ and applying the already proven inequality (1.80) with $\sigma = -(\ell-1)p < 0$ and the sequence $Su \in \mathcal{H}_0^1$, we further estimate

$$\sum_{n=\ell-1}^{\infty} \frac{|\operatorname{div} u_n|^p}{n^{(\ell-1)p}} = \sum_{n=1}^{\infty} \frac{|\nabla S u_n|^p}{n^{(\ell-1)p}} \geq C_p^{((1-\ell)p)} \sum_{n=1}^{\infty} \frac{|S u_n|^p}{(n+1)^{\ell p}}.$$

Shifting the index in the last sum and noticing that $B_p^{(\ell-1)} C_p^{((1-\ell)p)} = B_p^{(\ell)}$, see formulas (1.71) and (1.79), the above inequalities combine to

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n|^p \geq B_p^{(\ell)} \sum_{n=\ell}^{\infty} \frac{|u_n|^p}{n^{\ell p}}.$$

The proof of inequality (1.69) is complete. $\square$

1.4.3 Continuous p -Birman inequality

In this section, we derive the continuous p -Birman inequality from its discrete counterpart (1.69), following an approach utilized for $p = 2$ in [24]. Beyond the fact that the transition from discrete to continuous inequalities is interesting in itself, this step is motivated by two other objectives. First, it provides an alternative proof of the p -Birman inequality to the standard procedure, which naturally avoids the discrete formulation and is indicated in Remark 1.49. Second, in Remark 1.50, we take advantage of this passage to prove the optimality of constants in Theorems 1.38 and 1.44.

Theorem 1.46 (continuous p -Birman inequality). *Let $\ell \in \mathbb{N}$ and $p > 1$. Then the inequality*

$$\int_0^\infty |\varphi^{(\ell)}(x)|^p dx \geq \left(\frac{p-1}{p} \right)_\ell^p \int_0^\infty \frac{|\varphi(x)|^p}{x^{\ell p}} dx, \quad (1.85)$$

holds for all $\varphi \in C_0^\infty(\mathbb{R}_+)$ and the constant appearing on the right-hand side is optimal.

The proof will be developed progressively over the course of this section. We begin by establishing inequality (1.85), after which we demonstrate the optimality of the p -Birman constant $B_p^{(\ell)}$ in (1.85). Prior to the proof of inequality (1.85), we state a preparatory lemma that relates the discrete derivatives to the continuous ones.

Lemma 1.47. *For $N > 0$, $n \in \mathbb{N}_0$, and $\varphi \in C_0^\infty(\mathbb{R}_+)$, we denote $v_n^N := \varphi(n/N)$. Then for any $\ell \in \mathbb{N}$, we have*

$$\nabla^\ell v_n^N = \frac{1}{N^\ell} \varphi^{(\ell)}\left(\frac{n}{N}\right) + \mathcal{O}\left(\frac{1}{N^{\ell+1}}\right), \quad \text{as } N \rightarrow \infty,$$

uniformly for all $n \geq \ell$, i.e. the constant hidden in the Landau $\mathcal{O}$ -symbol is n -independent.

Proof. By definition (1.7), we have

$$\nabla^\ell v_n^N = \sum_{k=0}^{\ell} (-1)^k \binom{\ell}{k} v_{n-k}^N.$$

Moreover, applying the Taylor–Lagrange formula, we obtain

$$v_{n-k}^N = \varphi\left(\frac{n-k}{N}\right) = \sum_{j=0}^{\ell} \frac{1}{j!} \varphi^{(j)}\left(\frac{n}{N}\right) \left(\frac{-k}{N}\right)^j + \mathcal{O}\left(\frac{1}{N^{\ell+1}}\right),$$

where the constant in the Landau $\mathcal{O}$ -symbol can be taken n -independent since $\varphi \in C_0^\infty(\mathbb{R}_+)$. It follows that

$$\begin{aligned} \nabla^\ell v_n^N &= \sum_{k=0}^{\ell} (-1)^k \binom{\ell}{k} \left[\sum_{j=0}^{\ell} \frac{1}{j!} \varphi^{(j)}\left(\frac{n}{N}\right) \left(\frac{-k}{N}\right)^j + \mathcal{O}\left(\frac{1}{N^{\ell+1}}\right) \right] \\ &= \sum_{j=0}^{\ell} \frac{(-1)^j}{j!} \left[\sum_{k=0}^{\ell} (-1)^k \binom{\ell}{k} k^j \right] \frac{1}{N^j} \varphi^{(j)}\left(\frac{n}{N}\right) + \mathcal{O}\left(\frac{1}{N^{\ell+1}}\right), \end{aligned}$$

as $N \rightarrow \infty$, uniformly in $n \geq \ell$. Now, it suffices to apply the identity [13, Eq. (26.8.6)]

$$\sum_{k=0}^{\ell} (-1)^k \binom{\ell}{k} k^j = \begin{cases} 0 & \text{for } j < \ell, \\ (-1)^\ell \ell! & \text{for } j = \ell, \end{cases}$$

to the term in the square brackets to finish the proof. $\square$

Proof (of inequality (1.85)). First, notice that, by scaling of the variable x in both sides of (1.85), it is sufficient to prove the inequality for test functions φ supported in $(0, 1)$.

Fix $\varphi \in C_0^\infty(0, 1)$, $\ell \in \mathbb{N}$, and define $v_n^N := \varphi(n/N)$ for all $n \in \mathbb{N}_0$ and $N > 0$ sufficiently large, such that $v_n^N = 0$ for $n < \ell$. Since also $v_n^N = 0$ for all $n > N$, applying Lemma 1.47, we infer that

$$\sum_{n=\ell}^{\infty} |\nabla^\ell v_n^N|^p = \sum_{n=1}^N |\nabla^\ell v_n^N|^p = \sum_{n=1}^N \left| \frac{1}{N^\ell} \varphi^{(\ell)}\left(\frac{n}{N}\right) + \mathcal{O}\left(\frac{1}{N^{\ell+1}}\right) \right|^p = \frac{1}{N^{\ell p}} \sum_{n=1}^N \left| \varphi^{(\ell)}\left(\frac{n}{N}\right) \right|^p + \mathcal{O}\left(\frac{1}{N^{\ell p}}\right),$$

as $N \rightarrow \infty$. For the sequence $u^N := N^{\ell-1/p} v^N$ it follows that

$$\sum_{n=\ell}^{\infty} |\nabla^\ell u_n^N|^p = \frac{1}{N} \sum_{n=1}^N \left| \varphi^{(\ell)}\left(\frac{n}{N}\right) \right|^p + \mathcal{O}\left(\frac{1}{N}\right), \quad \text{as } N \rightarrow \infty.$$

Since also $u_n^N = 0$ for $n < \ell$ and $n > N$, we may apply the discrete p -Birman inequality (1.69) to obtain

$$\sum_{n=1}^N \frac{1}{N} \left| \varphi^{(\ell)}\left(\frac{n}{N}\right) \right|^p + \mathcal{O}\left(\frac{1}{N}\right) \geq \left(\frac{p-1}{p}\right)_\ell^p \sum_{n=\ell}^{\infty} \frac{|u_n^N|^p}{n^{\ell p}} = \left(\frac{p-1}{p}\right)_\ell^p \sum_{n=1}^N \frac{1}{N} \frac{|\varphi(n/N)|^p}{(n/N)^{\ell p}}$$

for $N \rightarrow \infty$. Recognizing the Riemann sums and taking the limit $N \rightarrow \infty$ in the above inequality, we arrive at the desired integral inequality (1.85). $\square$

Remark 1.48. We remark, without going into details, that one can proceed analogously as in the proof of inequality (1.85), using, this time, the sampling sequence

$$u_n^N := N^{1-(\sigma+1)/p} \varphi\left(\frac{n}{N}\right),$$

to deduce from (1.78) and (1.80) their continuous counterpart

$$\int_0^\infty x^\sigma |\varphi'(x)|^p dx \geq \left(\frac{p-\sigma-1}{p}\right)^p \int_0^\infty x^{\sigma-p} |\varphi(x)|^p dx, \quad (1.86)$$

which holds for all $\varphi \in C_0^\infty(\mathbb{R}_+)$ and $\sigma < p-1$ (the continuous limit takes the same form regardless of the sign of σ).

Remark 1.49. An integral form of the inequality (1.86) appeared already in the classical book by Hardy, Littlewood, and Pólya [22, Theorem 330], see also [30, Theorem 2]. The continuous p -Birman inequality (1.85) can be quickly proved through an iterative application of (1.86). Specifically, starting with the ℓ -th derivative of a test function φ and selecting $\sigma = -(j-1)p$ in the j -th step for any $j \in \{1, \dots, \ell\}$, the result follows directly.

Proof (of optimality of the p -Birman constant $B_p^{(\ell)}$ in Theorem 1.46). We verify the optimality of the constant $B_p^{(\ell)}$ in the continuous p -Birman inequality (1.85), which amounts to proving

$$\inf_{0 \neq \varphi \in C_0^\infty(\mathbb{R}_+)} \frac{\int_0^\infty |\varphi^{(\ell)}(x)|^p dx}{\int_0^\infty |\varphi(x)|^p / x^{\ell p} dx} = B_p^{(\ell)} \quad (1.87)$$

by construction of an approximating sequence of test functions $\varphi_N \in C_0^\infty(\mathbb{R}_+)$, for which the ratio in the infimum converges to $B_p^{(\ell)}$ as $N \rightarrow \infty$. Concretely for $N > 2$ and $x > 0$, we set

$$\varphi_N(x) := x^{\ell-1/p} \xi_N(x), \quad (1.88)$$

with the cut-off function $\xi_N \in C_0^\infty(\mathbb{R}_+)$ satisfying

$$\xi_N(x) = \begin{cases} 1 & \text{if } x \in [2/N, 1], \\ 0 & \text{if } x \in \mathbb{R}_+ \setminus [1/N, 2], \end{cases} \quad \text{and} \quad |\xi_N^{(j)}(x)| \leq \begin{cases} CN^j & \text{if } x \in [1/N, 2/N], \\ C & \text{if } x \in [1, 2], \end{cases} \quad (1.89)$$

for all $j \in \{0, \dots, \ell\}$, where $C > 0$ is a constant. Such a function can be constructed, for instance, as

$$\xi_N(x) := \eta(Nx-1)\eta(2-x),$$

where η is a smooth function on $\mathbb{R}$ satisfying $\eta(x) = 0$ for $x \leq 0$ and $\eta(x) = 1$ for $x \geq 1$. This regularization has been utilized in a slightly different situation in [35, Note 2.6].

Using the Leibniz rule, we estimate the L^p -norm of the ℓ -th derivative of φ_N as

$$\left(\int_0^\infty |\varphi_N^{(\ell)}(x)|^p dx\right)^{1/p} \leq \sum_{j=0}^{\ell} \binom{\ell}{j} \left(1 - \frac{1}{p} + j\right)_{\ell-j} \left(\int_0^\infty |x^{j-1/p} \xi_N^{(j)}(x)|^p dx\right)^{1/p}.$$

Employing the properties (1.89), we further estimate the integrals in the last sum separately for $j = 0$ and $j \in \{1, \dots, \ell\}$. For $j = 0$, we have

$$\int_0^\infty |x^{-1/p} \xi_N(x)|^p dx \leq C^p \int_{1/N}^{2/N} \frac{dx}{x} + \int_{2/N}^1 \frac{dx}{x} + C^p \int_1^2 \frac{dx}{x} = 2C^p \log 2 + \log(N/2),$$

while for $j \in \{1, \dots, \ell\}$, we obtain

$$\int_0^\infty |x^{j-1/p} \xi_N^{(j)}(x)|^p dx \leq C^p N^{jp} \int_{1/N}^{2/N} x^{jp-1} dx + C^p \int_1^2 x^{jp-1} dx = 2C^p \frac{2^{jp} - 1}{jp}.$$

Recalling formula (1.71), we obtain the upper bound

$$\left(\int_0^\infty |\varphi_N^{(\ell)}(x)|^p dx \right)^{1/p} \leq \left[B_p^{(\ell)} (A_0 + \log(N/2)) \right]^{1/p} + A_1,$$

where A_0 and A_1 are N -independent constants. Conversely, we find

$$\int_0^\infty \frac{|\varphi_N(x)|^p}{x^{\ell p}} dx \geq \int_{2/N}^1 \frac{dx}{x} = \log(N/2).$$

Altogether, bearing the continuous p -Birman inequality (1.85) in mind, we have

$$B_p^{(\ell)} \leq \frac{\int_0^\infty |\varphi_N^{(\ell)}(x)|^p dx}{\int_0^\infty |\varphi_N(x)|^p / x^{\ell p} dx} \leq \frac{\left(\left[B_p^{(\ell)} (A_0 + \log(N/2)) \right]^{1/p} + A_1 \right)^p}{\log(N/2)} \longrightarrow B_p^{(\ell)}, \quad \text{as } N \rightarrow \infty,$$

which yields (1.87). The proof of Theorem 1.46 is complete. $\square$

Remark 1.50. The proof of the continuous p -Birman inequality shows that inequality (1.85) follows from (1.69) regardless of the explicit form of the constant $B_p^{(\ell)}$. Consequently, the optimality of the constant $B_p^{(\ell)}$ defined by (1.71) in the continuous p -Birman inequality (1.85) immediately implies its optimality in the discrete counterpart (1.69).

Moreover, the proof of the optimality of the Copson constant $C_p^{(\sigma)}$ in the continuous inequality (1.86), and consequently in the discrete counterparts (1.78) and (1.80), follows a similar argument to the one detailed above. In this case, the test functions (1.88) are replaced by

$$\varphi_N(x) := x^{1-(\sigma+1)/p} \xi_N(x).$$

The sharpness within a space of non-smooth functions is also proved in [30, Theorem 2(iii)].

Chapter 2

Fractional Birman inequalities

Historically, higher-dimensional Hardy inequalities have attracted substantial attention because they provide information on the spectral properties of the Laplace operator, which are closely related to the transiency of Brownian motion described via the heat equation. It is a classical result that a Brownian particle in $\mathbb{R}^d$ almost surely leaves any bounded set and never returns if and only if $d \geq 3$. Conversely, Brownian motion in $\mathbb{R}$ and $\mathbb{R}^2$ is recurrent.

In parallel, the positive self-adjoint realization of the Laplacian $-\Delta$ on the Lebesgue space $L^2(\mathbb{R}^d)$ is *subcritical*—that is, there exists a non-trivial Hardy weight ρ such that $-\Delta \geq \rho$ in the sense of quadratic forms—whenever $d \geq 3$, whereas it is *critical* (i.e. not subcritical) for $d \in \{1, 2\}$.

An analogous criticality transition arises also in the setting of fractional positive powers of the one-dimensional Laplacian $(-\Delta_{\mathbb{R}})^\alpha$, for $\alpha \in (0, 1)$. Such nonlocal operators play a fundamental role in the analysis of anomalous transport and diffusion processes [34], and they also appear in a range of physical models, including, for instance, the relativistic Schrödinger-type equation in [33]. There exist several equivalent definitions of the fractional powers of the Laplace operator. In particular, [31] provides ten mutually equivalent characterizations of the fractional Laplacian on $\mathbb{R}^d$. Among these, we recall the definition via the Fourier transform (an analogous definition will be used for discrete Laplacians)

$$(-\Delta_{\mathbb{R}})^\alpha \varphi(x) := \mathcal{F}^{-1}[|\xi|^{2\alpha} \mathcal{F}\varphi(\xi)](x), \quad \text{for all } x \in \mathbb{R}, \quad (2.1)$$

as well as the characterization in terms of the associated quadratic form

$$\langle \varphi, (-\Delta_{\mathbb{R}})^\alpha \varphi \rangle_{L^2(\mathbb{R})} := \frac{4^\alpha \Gamma(\alpha + 1/2)}{2\sqrt{\pi} |\Gamma(-\alpha)|} \int_{\mathbb{R}^2} \frac{|\varphi(x) - \varphi(y)|^2}{|x - y|^{1+2\alpha}} dx dy, \quad (2.2)$$

valid for all $\varphi \in C_0^\infty(\mathbb{R})$. In [23], it was observed that the operator $(-\Delta_{\mathbb{R}})^\alpha$ is subcritical in $L^2(\mathbb{R})$ if and only if $\alpha \in (0, 1/2)$, in which case the *fractional Hardy inequality* $(-\Delta_{\mathbb{R}})^\alpha \geq \rho_\alpha^{\text{He}}$ holds with the weight

$$\rho_\alpha^{\text{He}}(x) := 4^\alpha \left[\frac{\Gamma(\frac{1+2\alpha}{4})}{\Gamma(\frac{1-2\alpha}{4})} \right]^2 \frac{1}{|x|^{2\alpha}}, \quad \text{for all } x \in \mathbb{R}.$$

The optimality of the constant was proved in [41].

The discrete analog on $\mathbb{Z}$ completely resembles the continuous setting. The fractional powers of the discrete Laplacian (1.5) admit a non-trivial Hardy inequality $(-\Delta)^\alpha \geq \rho_\alpha^{\text{CR}}$ with the null-critical weight

$$\rho_\alpha^{\text{CR}}(n) := 4^\alpha \left[\frac{\Gamma(\frac{1+2\alpha}{4})}{\Gamma(\frac{1-2\alpha}{4})} \right]^2 \frac{\Gamma(|n| + \frac{1-2\alpha}{4}) \Gamma(|n| + \frac{3-2\alpha}{4})}{\Gamma(|n| + \frac{1+2\alpha}{4}) \Gamma(|n| + \frac{3+2\alpha}{4})}, \quad \text{for all } n \in \mathbb{Z},$$

for all $\alpha \in (0, 1/2)$ as was shown in [6, 25]. In contrast, $(-\Delta)^\alpha$ is critical in $\ell^2(\mathbb{Z})$ for all $\alpha \geq 1/2$. Note that the leading term of the asymptotic expansion, as $|n| \rightarrow \infty$, is identical to the continuous analog ρ_α^{He} .

The situation on the half-line is more subtle, as there exist several non-equivalent definitions of general positive powers of the Laplace operator. In particular, due to the inherently nonlocal nature of fractional derivatives, the definition depends on whether the functions, resp. sequences, are formally extended by zero to the negative half-axis or are instead treated without such an extension. We first briefly discuss relevant results in the latter setting, after which we turn our attention to the former option, which will be considered in the remainder of the thesis.

In the continuum, the positive fractional powers of the half-line Laplacian $(-\Delta_{\mathbb{R}_+})^\alpha$, defined for $\alpha \in (0, 1)$ via its quadratic form

$$\langle \varphi, (-\Delta_{\mathbb{R}_+})^\alpha \varphi \rangle_{L^2(\mathbb{R}_+)} := \frac{4^\alpha \Gamma(\alpha + 1/2)}{2\sqrt{\pi} |\Gamma(-\alpha)|} \int_{\mathbb{R}_+^2} \frac{|\varphi(x) - \varphi(y)|^2}{|x - y|^{1+2\alpha}} dx dy$$

for all $\varphi \in C_0^\infty(\mathbb{R}_+)$ (compare with (2.2)), were analyzed in [5]. In this paper, the authors found the Hardy inequality $(-\Delta_{\mathbb{R}_+})^\alpha \geq \rho_\alpha^{\text{BD}}$ with the weight

$$\rho_\alpha^{\text{BD}}(x) := \frac{\Gamma^2(\alpha + 1/2) - \Gamma(2\alpha) \sin(\pi\alpha)}{\pi} \frac{1}{x^{2\alpha}}, \quad \text{for all } x > 0.$$

While the constant is optimal for all $\alpha \in (0, 1)$, it is only positive if $\alpha \neq 1/2$. The case $\alpha = 1/2$ was studied, for example, in [1].

In the discrete setting, the corresponding operator $(-\Delta_{\mathbb{N}})^\alpha$ was investigated for all $\alpha > 0$ in [18], where the authors established that the operator $(-\Delta_{\mathbb{N}})^\alpha$ is subcritical if and only if $\alpha < 3/2$. Furthermore, for this range of the parameter α , they explicitly identified Hardy weights of the form

$$\rho_\alpha^{\text{GKS}}(n) := \begin{cases} \frac{c(\alpha)}{n^{2\alpha}} & \text{if } \alpha \neq 1/2, \\ \frac{c(1/2)}{n \log n} & \text{if } \alpha = 1/2, \end{cases} \quad \text{for all } n \geq 1,$$

where $c(\alpha)$ is a positive constant depending on α , which was specified therein. Observe that for $\alpha \neq 1/2$ the Hardy weights decay as $n^{-2\alpha}$ in the limit $n \rightarrow \infty$, matching the asymptotic behavior of their continuous counterpart. For $\alpha \in (0, 1]$, the weights have recently been refined in [11]. In this regime, the null-critical Hardy weights are given in the form of the Gamma ratios

$$\rho_\alpha^{\text{DF}}(n) := 4^\alpha \left[\frac{\Gamma(\frac{3+2\alpha}{4})}{\Gamma(\frac{3-2\alpha}{4})} \right]^2 \frac{\Gamma(n + \frac{5-2\alpha}{4}) \Gamma(n - \frac{1+2\alpha}{4})}{\Gamma(n + \frac{5+2\alpha}{4}) \Gamma(n - \frac{1-2\alpha}{4})} \quad \text{for all } n \in \mathbb{N}.$$

Interestingly, these weights exhibit asymptotic decay $n^{-2\alpha}$, as $n \rightarrow \infty$, for every $\alpha \in (0, 1]$, including the critical value $\alpha = 1/2$.

On the other hand, if we regard the test functions on $\mathbb{R}_+$ to be formally extended by zero to the negative half-axis, the fractional Hardy inequality

$$\langle \varphi, (-\Delta_{\mathbb{R}})^\alpha \varphi \rangle = \int_0^\infty \overline{\varphi(x)} (-\Delta_{\mathbb{R}})^\alpha \varphi(x) dx \geq \frac{\Gamma^2(\alpha + 1/2)}{\pi} \int_0^\infty \frac{|\varphi(x)|^2}{x^{2\alpha}} dx,$$

where the operator $(-\Delta_{\mathbb{R}})^\alpha$ is defined by (2.1), was established in [5] for all $\varphi \in C_0^\infty(\mathbb{R}_+)$ and $\alpha \in (0, 1)$.

Remark 2.1. In fact, the Fourier transform definition (2.1) of the Laplacian on $\mathbb{R}$ can be extended to all $\alpha > 0$ and $\varphi \in C_0^\infty(\mathbb{R})$ as

$$(-\Delta_{\mathbb{R}})^\alpha \varphi(x) := \mathcal{F}^{-1} [|\xi|^{2(\alpha - [\alpha])} (i\xi)^{2[\alpha]} \mathcal{F}\varphi(\xi)](x), \quad \text{for all } x \in \mathbb{R}, \quad (2.3)$$

where $\lfloor \nu \rfloor$ denotes the largest integer smaller than or equal to $\nu \in \mathbb{R}$. Consequently, invoking the latter fractional Hardy inequality for the $\lfloor \alpha \rfloor$ -th derivative of $\varphi \in C_0^\infty(\mathbb{R}_+)$, we have

$$\langle \varphi, (-\Delta_{\mathbb{R}})^\alpha \varphi \rangle = \langle \varphi^{(\lfloor \alpha \rfloor)}, (-\Delta_{\mathbb{R}})^{\alpha - \lfloor \alpha \rfloor} \varphi^{(\lfloor \alpha \rfloor)} \rangle \geq \frac{\Gamma^2(\alpha - \lfloor \alpha \rfloor + 1/2)}{\pi} \int_0^\infty \frac{|\varphi^{(\lfloor \alpha \rfloor)}(x)|^2}{x^{2(\alpha - \lfloor \alpha \rfloor)}} dx.$$

Iteratively applying the continuous Copson inequality (1.86) with $\sigma = -2(\alpha - \lfloor \alpha \rfloor + j - 1)$ in the j -th step for $j \in \{1, \dots, \lfloor \alpha \rfloor\}$, we obtain the *fractional Birman inequality*

$$\int_0^\infty \overline{\varphi(x)} (-\Delta_{\mathbb{R}})^\alpha \varphi(x) dx \geq \left(\frac{1}{2}\right)_\alpha^2 \int_0^\infty \frac{|\varphi(x)|^2}{x^{2\alpha}} dx \quad (2.4)$$

for all $\alpha > 0$ and $\varphi \in C_0^\infty(\mathbb{R}_+)$. Here, the *generalized Pochhammer symbol* is introduced in the form

$$(\nu)_\lambda := \frac{\Gamma(\nu + \lambda)}{\Gamma(\nu)} \quad \text{for all } \nu, \lambda > 0, \quad (2.5)$$

in order to replicate the structure of the constants appearing in the continuous p -Birman inequality (1.1). To the best of our knowledge, the inequality (2.4) has not previously appeared in the literature for non-integer parameters $\alpha > 1$, while for $\alpha = \ell \in \mathbb{N}$, it coincides with the classical result of Birman (3).

Surprisingly, the existing literature does not appear to address the discrete analog of the fractional Laplacian, defined in (2.3), when restricted to functions supported on the half-line $\mathbb{R}_+$. The purpose of this chapter is to close this gap by deriving a discrete counterpart of the inequality (2.4) for the operator $(-\Delta)^\alpha$.

The chapter is structured as follows:

- In Section 2.1, we define general positive powers $(-\Delta)^\alpha$, for $\alpha > 0$, of the discrete Laplacian (1.5) on $\mathbb{Z}$ and examine several of their fundamental properties. In particular, we derive the matrix representation with respect to the standard basis and analyze the corresponding matrix elements.
- In Section 2.2, we devise a method for constructing abstract fractional Birman weights associated with a parameter sequence $\mathbf{g}$ that satisfies certain sufficient conditions. The main idea is to first establish a fractional Hardy inequality for $\alpha \in (0, 1]$, which is subsequently iterated with the aid of the first-order weighted Hardy equality (1.14).
- In Section 2.3, we apply the abstract framework developed in Section 2.2 to the parameter sequence $\mathbf{g}^{(\alpha)}$, given by formula (2.23), and thereby derive explicit fractional Birman inequalities for all $\alpha > 0$ in Theorem 2.14. By obtaining a suitable lower bound for the relevant weight sequence, we obtain a complete discrete counterpart of the continuous inequality (2.4).
- Finally, in Section 2.4, we briefly analyze the optimality properties of the explicit fractional Birman weights $\rho^{(\alpha)}$ obtained in Section 2.3.

2.1 Positive powers of the discrete Laplacian on $\mathbb{Z}$

Recall that the discrete Laplace operator on $\ell^2(\mathbb{Z})$ is determined by the bi-infinite Toeplitz matrix

$$-\Delta = \begin{pmatrix} \ddots & \ddots & \ddots & & & \\ & -1 & 2 & -1 & & \\ & & -1 & 2 & -1 & \\ & & & -1 & 2 & -1 \\ & & & & \ddots & \ddots & \ddots \end{pmatrix},$$

with respect to the standard basis $\{\delta_n\}_{n \in \mathbb{Z}}$, that is, $-\Delta u_n = -u_{n-1} + 2u_n - u_{n+1}$ for every $u \in \ell^2(\mathbb{Z})$ and $n \in \mathbb{Z}$. We define its general positive powers by diagonalizing $-\Delta$ via the discrete Fourier transform, in direct analogy with (2.1), following the approach outlined in [18]. An equivalent formulation based on the spectral calculus can be found in [25].

Let $\mathcal{F} : \ell^2(\mathbb{Z}) \rightarrow L^2(-\pi, \pi)$ denote the unitary operator specified by its action on the standard basis $\{\delta_n\}_{n \in \mathbb{Z}}$, namely $\mathcal{F}\delta_n := f_n$, where $\{f_n\}_{n \in \mathbb{Z}}$ is the orthonormal basis of the Hilbert space $L^2(-\pi, \pi)$ given by

$$f_n(x) := \frac{1}{\sqrt{2\pi}} e^{inx} \quad \text{for all } x \in (-\pi, \pi).$$

Under this Fourier transform, the discrete Laplacian $-\Delta$ on $\ell^2(\mathbb{Z})$ is unitarily equivalent to a multiplication operator on $L^2(-\pi, \pi)$. More precisely, its action on the basis elements $\{f_n\}_{n \in \mathbb{Z}}$ is given by

$$(\mathcal{F}(-\Delta)\mathcal{F}^{-1}f_n)(x) = \frac{1}{\sqrt{2\pi}} e^{-inx} (-e^{-ix} + 2 - e^{ix}) = (2 - 2\cos x)f_n(x) = M_{2-2\cos x}f_n(x),$$

for all $n \in \mathbb{Z}$ and $x \in (-\pi, \pi)$, where $M_{\varphi(x)}$ denotes the multiplication operator by the function $x \mapsto \varphi(x)$. Consequently, we may define the positive powers of the discrete Laplace operator by

$$(-\Delta)^\alpha := \mathcal{F}^{-1}M_{(2-2\cos x)^\alpha}\mathcal{F} \quad \text{for all } \alpha > 0. \quad (2.6)$$

We now proceed to compute the matrix elements of these operators. For this purpose, we introduce the generalized binomial coefficient, defined by

$$\binom{a}{b} := \frac{\Gamma(a+1)}{\Gamma(b+1)\Gamma(a-b+1)} \quad \text{for all } a > -1 \text{ and } b \in \mathbb{R}. \quad (2.7)$$

(Recall that the reciprocal Gamma function is an entire function vanishing at the points $0, -1, \dots$.)

Proposition 2.2. *Let $\alpha > 0$. Then the operator $(-\Delta)^\alpha$ acting on $\ell^2(\mathbb{Z})$ is represented by a bi-infinite symmetric Toeplitz matrix whose entries read*

$$(-\Delta)_{mn}^\alpha = (-1)^{m+n} \binom{2\alpha}{\alpha + m - n} \quad \text{for all } m, n \in \mathbb{Z}. \quad (2.8)$$

Proof. By definition (2.6) of the operator $(-\Delta)^\alpha$ and unitarity of the discrete Fourier transform $\mathcal{F}$, we have

$$(-\Delta)_{mn}^\alpha = \langle \delta_m, (-\Delta)^\alpha \delta_n \rangle = \langle f_m, M_{(2-2\cos x)^\alpha} f_n \rangle = \frac{1}{2\pi} \int_{-\pi}^{\pi} (2-2\cos x)^\alpha e^{i(n-m)x} dx.$$

Since the function $2-2\cos x = 4\sin^2(x/2)$ is even, the integral representation further simplifies to

$$(-\Delta)_{mn}^\alpha = 2 \frac{4^\alpha}{\pi} \int_0^{\pi/2} \sin^{2\alpha} t \cos 2(m-n)t dt,$$

where we used the substitution $x = 2t$. The latter integral may be computed with the aid of a slight modification of the identity [21, § 3.631, Eq. (8)], which reads

$$\int_0^{\pi/2} \sin^{\nu-1}(t) \cos(2\ell t) dt = \frac{(-1)^\ell \pi \Gamma(\nu)}{2^\nu \Gamma(\frac{\nu+1}{2} + \ell) \Gamma(\frac{\nu+1}{2} - \ell)} \quad \text{for all } \ell \in \mathbb{Z} \text{ and } \operatorname{Re} \nu > 0.$$

Altogether, in view of definition (2.7), we obtain the desired result

$$(-\Delta)_{mn}^\alpha = (-1)^{m+n} \frac{\Gamma(2\alpha+1)}{\Gamma(\alpha+1+m-n)\Gamma(\alpha+1-m+n)} = (-1)^{m+n} \binom{2\alpha}{\alpha+m-n}$$

for all $m, n \in \mathbb{Z}$. The symmetry of the matrix follows directly from the middle expression. $\square$

Remark 2.3. By applying the *Euler reflection formula* [13, Eq. (5.5.1)]

$$\Gamma(z)\Gamma(1-z) = \pi / \sin(\pi z), \quad (2.9)$$

which holds for all $z \notin \mathbb{Z}$, we further obtain

$$(-\Delta)_{mn}^\alpha = -\frac{\Gamma(2\alpha+1)\sin(\pi\alpha)}{\pi} \frac{\Gamma(m-n-\alpha)}{\Gamma(m-n+\alpha+1)} \quad (2.10)$$

for all $m, n \in \mathbb{Z}$ and all non-integer $\alpha > 0$.

Remark 2.4. In [18], the authors investigated fractional powers of the Laplace operator $(-\Delta_{\mathbb{N}})^\alpha$ for any $\alpha > 0$. The matrix elements of such an operator with respect to the standard basis of $\ell^2(\mathbb{N})$ read

$$(-\Delta_{\mathbb{N}})_{mn}^\alpha = (-1)^{m+n} \left[\binom{2\alpha}{\alpha+m-n} - \binom{2\alpha}{\alpha+m+n} \right] \quad \text{for all } m, n \in \mathbb{N}. \quad (2.11)$$

The corresponding matrix is no longer Toeplitz and differs from $(-\Delta)^\alpha|_{\ell^2(\mathbb{N})}$ by a Hankel matrix.

In order to preserve the notation introduced in Chapter 1 and specified in Section 1.1, we do not restrict the operator $(-\Delta)^\alpha$ to the Hilbert space $\ell^2(\mathbb{N})$. Instead, we consider it on the spaces $\mathcal{H}_0^1$ and $\mathcal{H}^{1,2} \equiv \ell^2(\mathbb{N})$, highlighting that the sequences are formally extended by zero to negative indices; see the definitions in (1.6). We further extend this definition to all sequences for which the series in

$$(-\Delta)^\alpha u_n := \sum_{m=1}^{\infty} (-\Delta)_{nm}^\alpha u_m \quad (2.12)$$

converges absolutely for every $n \in \mathbb{N}$, that is, to the domain

$$\mathcal{D}_\alpha := \left\{ v \in H^1 \mid \sum_{m=1}^{\infty} |(-\Delta)_{nm}^\alpha v_m| < \infty, \forall n \in \mathbb{N} \right\}.$$

Observe that the asymptotic expansion (1.59), in conjunction with the formula (2.10), yields the estimate

$$|(-\Delta)_{mn}^\alpha| \lesssim \frac{1}{|m-n|^{2\alpha+1}} \quad \text{for all } m \neq n, \quad (2.13)$$

where, this time, the hidden constant may depend on α but is independent of m and n . In particular, this implies the embeddings $\mathcal{H}^{1,2} = H^1 \cap \ell^2(\mathbb{Z}) \subset H^1 \cap \ell^\infty(\mathbb{Z}) \subset \mathcal{D}_\alpha$ for every $\alpha > 0$.

In [11], the authors exploit the fact that the fractional Laplacian $(-\Delta_{\mathbb{N}})^\alpha$, determined by (2.11), can be interpreted as a formal Schrödinger operator on a suitable nonlocal graph for $\alpha \in (0, 1]$. This observation allows them to apply the abstract framework of optimal Hardy inequalities on graphs developed in [27]. For completeness, we demonstrate that the Laplacian $(-\Delta)^\alpha$, defined by (2.12), likewise induces a formal Schrödinger operator for $\alpha \in (0, 1]$ in the following sense. A *graph* over a discrete set X is a symmetric function $e : X \times X \rightarrow [0, \infty)$, such that

$$e(x, x) = 0 \quad \text{and} \quad \sum_{y \in X} e(x, y) < \infty \quad \text{for all } x \in X.$$

If $e(x, y) > 0$, we say that $x, y \in X$ are *connected by an edge* and write $x \sim y$. The *formal Laplacian* L , acting on the space

$$\mathcal{D}(X) := \left\{ u : X \rightarrow \mathbb{C} \mid \sum_{y \sim x} e(x, y) |u(y)| < \infty \forall x \in X \right\} \supset \ell^\infty(X),$$

where $\ell^\infty(X)$ denotes the set of bounded functions on X , is defined by the formula

$$Lu(x) := \sum_{y \sim x} e(x, y)(u(x) - u(y)) \quad \text{for all } x \in X.$$

Finally, the *formal Schrödinger operator* H associated with the potential $q : X \rightarrow \mathbb{R}$ is defined on $\mathcal{D}(X)$ by $H := L + q$, i.e. $Hu(x) := Lu(x) + q(x)u(x)$ for all $x \in X$ and $u \in \mathcal{D}(X)$.

We now set $X := \mathbb{N}$, define $e(m, n) := -(-\Delta)_{mn}^\alpha$ for all $m \neq n$, and $e(n, n) := 0$ for all $n \in \mathbb{N}$. The resulting graph is well-defined for every $\alpha \in (0, 1]$, since e is symmetric by Proposition 2.2 and non-negative by virtue of the formulas (2.8) for $\alpha = 1$, resp. (2.10) for $\alpha \in (0, 1)$, where, without loss of generality, it suffices to assume $m > n$. Moreover, we introduce the potential

$$q(n) := \sum_{m \in \mathbb{N}} (-\Delta)_{mn}^\alpha, \quad \text{for all } n \in \mathbb{N},$$

where the series converges absolutely by (2.13). Therefore, in view of definition (2.12), we obtain

$$(-\Delta)^\alpha u(n) := - \sum_{m=1}^{\infty} (-\Delta)_{nm}^\alpha (u(n) - u(m)) + u(n) \sum_{m=1}^{\infty} (-\Delta)_{nm}^\alpha \equiv Lu(n) + q(n)u(n), \quad (2.14)$$

and thus the operator $(-\Delta)^\alpha$ indeed induces a formal Schrödinger operator for all $\alpha \in (0, 1]$. Although this fact will not be used explicitly, it constitutes the main idea behind the *ground state transform* (cf. [27, Proposition 2.4]), given by the Hardy-type identity in Theorem 2.8 below.

Remark 2.5. The associated potential can be computed explicitly as

$$q(n) = \sum_{m=1}^{\infty} (-\Delta)_{mn}^\alpha = (-1)^{n+1} \binom{2\alpha - 1}{\alpha - n} \quad \text{for all } n \in \mathbb{N}, \quad (2.15)$$

in fact the latter identity holds for any $\alpha > 0$ and $n \in \mathbb{Z}$. Indeed, invoking the formula (2.8) and Pascal's rule

$$\binom{a-1}{b} + \binom{a-1}{b-1} = \binom{a}{b} \quad \text{valid for all } a > 0 \text{ and } b \in \mathbb{R},$$

the series becomes a *telescoping* sum of the form

$$\sum_{m=1}^{\infty} (-\Delta)_{mn}^\alpha = (-1)^n \sum_{m=1}^{\infty} (-1)^m (a_m + a_{m-1}), \quad \text{where } a_m := \binom{2\alpha - 1}{\alpha + m - n}.$$

We conclude that $(-1)^n q(n) = -a_0 + \lim_{N \rightarrow \infty} (-1)^N a_N = -a_0$, where in the last step we have used the estimate $|a_m| \lesssim m^{-2\alpha-1}$, which follows from the Euler reflection formula (2.9) in combination with the asymptotic expansion (1.59). This, however, coincides with the desired identity.

2.2 Abstract fractional Birman inequalities

In this section, we explain how to derive abstract fractional Birman inequalities for the operator $(-\Delta)^\alpha$, $\alpha > 0$, defined by (2.12). In analogy with Section 1.2, we consider a parameter sequence $\mathbf{g}$ and establish fractional Birman identities that are structurally analogous to (1.12) and (1.16), with the remainders expressed in terms of $\mathbf{g}$. Under additional assumptions imposed on $\mathbf{g}$, these remainders become nonnegative, thereby yielding the desired fractional Birman inequalities.

Let us begin by introducing the fractional Birman weights and the associated inequalities in accordance with Definition 1.1.

Definition 2.6. Let $\alpha > 0$. A non-negative sequence $\{\rho_n\}_{n=1}^\infty$ is called a *discrete fractional Birman weight* if and only if the *discrete fractional Birman inequality*

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^\alpha u_n \geq \sum_{n=1}^{\infty} \rho_n |u_n|^2 \quad (2.16)$$

holds for any $u \in \mathcal{H}_0^1$. In addition, the weight ρ is said to be *non-attainable* in $\mathcal{H}_0^1$ if, whenever the equality in (2.16) is attained for $u \in \mathcal{H}_0^1$, necessarily $u \equiv 0$.

Analogously to the continuous framework discussed in Remark 2.1, the key step in deriving fractional Birman inequalities for arbitrary $\alpha > 0$ is to first analyze the Hardy regime $\alpha \in (0, 1]$. After establishing this fundamental case, the result is then generalized to higher-order derivatives by means of an iterative application of the weighted first-order Hardy identity (1.14).

For this purpose, we begin by formulating the following auxiliary lemma, which, for $\alpha \in (0, 1]$, identifies the *quadratic form* associated with the formal Schrödinger operator (2.14) corresponding to the fractional Laplacian $(-\Delta)^\alpha$.

Lemma 2.7. *Let $\alpha > 0$. Then for any $u \in \mathcal{H}_0^1$, we have the identity*

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^\alpha u_n = -\frac{1}{2} \sum_{m,n \in \mathbb{N}} (-\Delta)_{nm}^\alpha |u_m - u_n|^2 - \sum_{n=1}^{\infty} (-1)^n \binom{2\alpha-1}{\alpha-n} |u_n|^2.$$

Proof. In light of definition (2.12), the quadratic form on the left-hand side can be rewritten as

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^\alpha u_n = \sum_{n=1}^{\infty} \overline{u_n} \sum_{m=1}^{\infty} (-\Delta)_{nm}^\alpha u_m = \sum_{n=1}^{\infty} \left(\sum_{m=1}^{\infty} (-\Delta)_{nm}^\alpha \right) |u_n|^2 - \sum_{m,n \in \mathbb{N}} (-\Delta)_{nm}^\alpha \overline{u_n} (u_n - u_m).$$

Invoking the symmetry of the operator $(-\Delta)^\alpha$, established in Proposition 2.2, we deduce that

$$\sum_{m,n \in \mathbb{N}} (-\Delta)_{nm}^\alpha \overline{u_n} (u_n - u_m) = \sum_{m,n \in \mathbb{N}} (-\Delta)_{nm}^\alpha \overline{u_m} (u_m - u_n) = \frac{1}{2} \sum_{m,n \in \mathbb{N}} (-\Delta)_{nm}^\alpha |u_m - u_n|^2.$$

The claim then follows directly from the identity (2.15). $\square$

We are now in position to derive fractional Birman identities for any $\alpha > 0$, analogous to the *ground state representation* [11, Proposition 3.4] of the operator $(-\Delta_{\mathbb{N}})^\alpha$ for $\alpha \in (0, 1]$.

Theorem 2.8. *Let $\alpha > 0$ and $\mathfrak{g} \in \mathcal{D}_\alpha$, such that $\mathfrak{g}_n > 0$ for all $n \geq 1$. Then for any $u \in \mathcal{H}_0^1$, we have the identity*

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^\alpha u_n - \sum_{n=1}^{\infty} \frac{(-\Delta)^\alpha \mathfrak{g}_n}{\mathfrak{g}_n} |u_n|^2 = - \sum_{1 \leq n < m} (-\Delta)_{mn}^\alpha \left| \sqrt{\frac{\mathfrak{g}_n}{\mathfrak{g}_m}} u_m - \sqrt{\frac{\mathfrak{g}_m}{\mathfrak{g}_n}} u_n \right|^2. \quad (2.17)$$

Proof. For any $m \neq n$, elementary computations yield

$$\begin{aligned} \left| \sqrt{\frac{\mathfrak{g}_n}{\mathfrak{g}_m}} u_m - \sqrt{\frac{\mathfrak{g}_m}{\mathfrak{g}_n}} u_n \right|^2 &= \frac{\mathfrak{g}_n}{\mathfrak{g}_m} |u_m|^2 + \frac{\mathfrak{g}_m}{\mathfrak{g}_n} |u_n|^2 - 2 \operatorname{Re} (\overline{u_n} u_m) \\ &= |u_m - u_n|^2 + \frac{\mathfrak{g}_n}{\mathfrak{g}_m} |u_m|^2 + \frac{\mathfrak{g}_m}{\mathfrak{g}_n} |u_n|^2 - |u_n|^2 - |u_m|^2. \end{aligned}$$

Multiplying both sides by $-(\Delta)_{mn}^\alpha/2$ and summing over all $m, n \in \mathbb{N}$, we obtain

$$\begin{aligned} - \sum_{1 \leq n < m} (-\Delta)_{mn}^\alpha \left| \sqrt{\frac{\mathfrak{g}_n}{\mathfrak{g}_m}} u_m - \sqrt{\frac{\mathfrak{g}_m}{\mathfrak{g}_n}} u_n \right|^2 &= -\frac{1}{2} \sum_{m, n \in \mathbb{N}} (-\Delta)_{nm}^\alpha |u_m - u_n|^2 - \sum_{n=1}^{\infty} (-1)^n \binom{2\alpha-1}{\alpha-n} |u_n|^2 \\ &\quad - \sum_{n=1}^{\infty} \frac{|u_n|^2}{\mathfrak{g}_n} \left(\sum_{m=1}^{\infty} (-\Delta)_{mn}^\alpha \mathfrak{g}_m \right), \end{aligned}$$

where we used the symmetry $(-\Delta)_{nm}^\alpha = (-\Delta)_{mn}^\alpha$ and the formula (2.15). Applying Lemma 2.7 to the first line of the right-hand side and employing definition (2.12) in the second, we arrive at the desired identity (2.17). $\square$

In analogy with Section 1.2, our goal is to ensure the non-negativity of the remainder term appearing on the right-hand side of the fractional Birman identity (2.17). However, according to formula (2.10), the inequality $(-\Delta)_{mn}^\alpha \leq 0$ is valid for all $m > n$ only when $\alpha \in (0, 1]$. To overcome this limitation, we combine Theorem 2.8 for $\alpha \in (0, 1]$ with an iteration of the weighted Hardy identity

$$\sum_{n=1}^{\infty} V_n |\nabla u_n|^2 + \sum_{n=1}^{\infty} \frac{\operatorname{div}(V \nabla \mathfrak{g})_n}{\mathfrak{g}_n} |u_n|^2 = \sum_{n=1}^{\infty} V_{n+1} \left| \sqrt{\frac{\mathfrak{g}_n}{\mathfrak{g}_{n+1}}} u_{n+1} - \sqrt{\frac{\mathfrak{g}_{n+1}}{\mathfrak{g}_n}} u_n \right|^2, \quad (2.18)$$

which holds for all $V \in C(\mathbb{N})$, $\mathfrak{g} \in H^1$ satisfying $\mathfrak{g}_n > 0$ for all $n \geq 1$, and $u \in \mathcal{H}_0^1$; see Remark 1.5. The iteration is reminiscent of the one used in the proof of Theorem 1.7 in Section 1.2.1.2.

For streamlined notation, we define

$$\{\nu\} := \nu - (\lceil \nu \rceil - 1) \quad \text{for all } \nu \in \mathbb{R},$$

that is, $\{\nu\}$ denotes the *fractional part* of ν , with the modified convention that integer arguments are mapped to 1 rather than 0.

Theorem 2.9. *Let $\alpha > 0$. Suppose that $\mathfrak{g} \in H^1$ satisfies the assumption*

$$\nabla^k \mathfrak{g} \in \mathcal{D}_{\alpha-k} \quad \text{with} \quad \nabla^k \mathfrak{g}_n > 0 \quad \text{for all } n \geq 1 \text{ and } k \in \{0, \dots, \lceil \alpha \rceil - 1\}. \quad (\text{A2.1})$$

Then for all $u \in \mathcal{H}_0^1$, we have the identity

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^\alpha u_n - \sum_{n=1}^{\infty} \frac{(-\Delta)^\alpha \mathfrak{g}_n}{\mathfrak{g}_n} |u_n|^2 = \sum_{k=1}^{\lceil \alpha \rceil} R_k^{(\alpha)}(\mathfrak{g}, u), \quad (2.19)$$

where the remainders are given by the formulas

$$R_k^{(\alpha)}(\mathfrak{g}, u) := \begin{cases} \sum_{n=1}^{\infty} \frac{(-\Delta)^{\alpha-k} \nabla^k \mathfrak{g}_{n+1}}{\nabla^k \mathfrak{g}_{n+1}} \left| \sqrt{\frac{\nabla^{k-1} \mathfrak{g}_n}{\nabla^{k-1} \mathfrak{g}_{n+1}}} \nabla^{k-1} u_{n+1} - \sqrt{\frac{\nabla^{k-1} \mathfrak{g}_{n+1}}{\nabla^{k-1} \mathfrak{g}_n}} \nabla^{k-1} u_n \right|^2 & \text{if } k < \lceil \alpha \rceil, \\ - \sum_{1 \leq n < m} (-\Delta)_{mn}^{\{\alpha\}} \left| \sqrt{\frac{\nabla^{\lceil \alpha \rceil - 1} \mathfrak{g}_n}{\nabla^{\lceil \alpha \rceil - 1} \mathfrak{g}_m}} \nabla^{\lceil \alpha \rceil - 1} u_m - \sqrt{\frac{\nabla^{\lceil \alpha \rceil - 1} \mathfrak{g}_m}{\nabla^{\lceil \alpha \rceil - 1} \mathfrak{g}_n}} \nabla^{\lceil \alpha \rceil - 1} u_n \right|^2 & \text{if } k = \lceil \alpha \rceil. \end{cases} \quad (2.20)$$

Proof. The proof proceeds by induction on $\lceil \alpha \rceil \in \mathbb{N}$ and follows the lines of the proof of Theorem 1.7 in Section 1.2.1.2. The base case $\lceil \alpha \rceil = 1$ coincides with Theorem 2.8.

Suppose $\lceil \alpha \rceil \geq 2$. Since $(-\Delta)^\alpha$ is a Toeplitz operator by Proposition 2.2, one readily verifies that it commutes with the shift operator S , defined in (1.8), and consequently also with the discrete divergence $\operatorname{div} = S - I$. Recalling that the adjoint of the discrete divergence operator is $\operatorname{div}^* = -\nabla$, we have

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^\alpha u_n = \sum_{n=1}^{\infty} \overline{\nabla u_n} (-\Delta)^{\alpha-1} \nabla u_n \quad \text{for any } u \in \mathcal{H}_0^1.$$

Consider $\mathbf{g} \in H^1$ satisfying assumption (A2.1). Evidently, $\nabla \mathbf{g} \in H^1$ fulfills the assumption for $\alpha - 1$, and therefore the induction hypothesis, applied to $\nabla u \in \mathcal{H}_0^1$, with $\nabla \mathbf{g}$, yields

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^{\alpha} u_n = \sum_{n=1}^{\infty} \frac{(-\Delta)^{\alpha-1} \nabla \mathbf{g}_n}{\nabla \mathbf{g}_n} |\nabla u_n|^2 + \sum_{k=1}^{\lceil \alpha \rceil - 1} R_k^{(\alpha-1)}(\nabla \mathbf{g}, \nabla u). \quad (2.21)$$

In view of the defining formula (2.20) of the remainders on the right-hand side, the obvious identity $\{\alpha\} = \{\alpha - 1\}$ implies, for all $k \in \{1, \dots, \lceil \alpha \rceil - 1\}$,

$$R_k^{(\alpha-1)}(\nabla \mathbf{g}, \nabla u) = R_{k+1}^{(\alpha)}(\mathbf{g}, u), \quad \text{thus} \quad \sum_{k=1}^{\lceil \alpha \rceil - 1} R_k^{(\alpha-1)}(\nabla \mathbf{g}, \nabla u) = \sum_{k=2}^{\lceil \alpha \rceil} R_k^{(\alpha)}(\mathbf{g}, u).$$

Next, invoking the identity (2.18) with the weight $V_n := (-\Delta)^{\alpha-1} \nabla \mathbf{g}_n / \nabla \mathbf{g}_n$ for all $n \in \mathbb{N}$, the first term on the right-hand side of (2.21) rewrites as

$$\sum_{n=1}^{\infty} \frac{(-\Delta)^{\alpha-1} \nabla \mathbf{g}_n}{\nabla \mathbf{g}_n} |\nabla u_n|^2 = - \sum_{n=1}^{\infty} \frac{\operatorname{div}(V \nabla \mathbf{g})_n}{\mathbf{g}_n} |u_n|^2 + \sum_{n=1}^{\infty} \frac{(-\Delta)^{\alpha-1} \nabla \mathbf{g}_{n+1}}{\nabla \mathbf{g}_{n+1}} \left| \sqrt{\frac{\mathbf{g}_n}{\mathbf{g}_{n+1}}} u_{n+1} - \sqrt{\frac{\mathbf{g}_{n+1}}{\mathbf{g}_n}} u_n \right|^2.$$

While the numerator of the prefactor in the first sum on the right-hand side of the latter identity simplifies as

$$-\operatorname{div}(V \nabla \mathbf{g}) = -\operatorname{div} \left(\frac{(-\Delta)^{\alpha-1} \nabla \mathbf{g}}{\nabla \mathbf{g}} \nabla \mathbf{g} \right) = (-\Delta)^{\alpha} \mathbf{g},$$

the second sum is equal to the remainder $R_1^{(\alpha)}(\mathbf{g}, u)$ by definition (2.20). Therefore,

$$\sum_{n=1}^{\infty} \frac{(-\Delta)^{\alpha-1} \nabla \mathbf{g}_n}{\nabla \mathbf{g}_n} |\nabla u_n|^2 = \sum_{n=1}^{\infty} \frac{(-\Delta)^{\alpha} \mathbf{g}_n}{\mathbf{g}_n} |u_n|^2 + R_1^{(\alpha)}(\mathbf{g}, u),$$

which, in combination with the identity (2.21), completes the proof of Theorem 2.9. $\square$

Now, by imposing additional assumptions on the parameter sequence $\mathbf{g}$, we may guarantee the non-negativity of the new remainder terms on the right-hand side of (2.19), as defined by (2.20), and thereby derive an abstract fractional discrete Birman inequality for any $\alpha > 0$. We regard the following theorem as the first principal result of this chapter.

Theorem 2.10. *Let $\alpha > 0$. Suppose that $\mathbf{g} \in H^1$ satisfies assumptions (A2.1), and, in addition*

$$(-\Delta)^{\alpha-k} \nabla^k \mathbf{g}_n \geq 0 \quad \text{for all } n \geq 2 \text{ and } k \in \{1, \dots, \lceil \alpha \rceil - 1\}. \quad (\text{A2.2})$$

Then for all $u \in \mathcal{H}_0^1$, we have the inequality

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^{\alpha} u_n \geq \sum_{n=1}^{\infty} \rho_n(\mathbf{g}) |u_n|^2, \quad (2.22)$$

where $\rho(\mathbf{g}) := (-\Delta)^{\alpha} \mathbf{g} / \mathbf{g}$. If moreover,

$$(-\Delta)^{\alpha} \mathbf{g}_n \geq 0 \quad \text{for all } n \geq 1, \quad (\text{A2.3})$$

then $\rho(\mathbf{g}) \geq 0$ is a discrete fractional Birman weight, which is non-attainable in $\mathcal{H}_0^1$.

Proof. Recalling the definition (2.20) of the remainders $R_k^{(\alpha)}(\mathbf{g}, u)$, assumption (A2.2) ensures their non-negativity for all $k \in \{1, \dots, \lceil \alpha \rceil - 1\}$. The non-negativity for $k = \lceil \alpha \rceil$ follows from the formula (2.10). Consequently, Theorem 2.9 implies the inequality (2.22). Furthermore, assumption (A2.3), i.e. the non-negativity of the sequence

$$\rho_n(\mathbf{g}) = (-\Delta)^\alpha \mathbf{g}_n / \mathbf{g}_n, \quad \text{for all } n \geq 1,$$

renders $\rho(\mathbf{g})$ a fractional Birman weight.

In order to prove the non-attainability in $\mathcal{H}_0^1$, we proceed analogously as in the proof of Theorem 1.9 in Section 1.2.1.3. Suppose that $u \in \mathcal{H}_0^1$ fulfills inequality (2.22) as equality. Theorem 2.9 implies that the remainders on the right-hand side of the identity (2.19) vanish for all $k \in \{1, \dots, \lceil \alpha \rceil\}$. In particular, since

$$-(-\Delta)_{n+1,n}^{\{\alpha\}} = \left(\frac{2\{\alpha\}}{\{\alpha\} + 1} \right) > 0 \quad \text{for all } n \geq 1,$$

for $k = \lceil \alpha \rceil$, we obtain the necessary condition

$$\sqrt{\frac{\nabla^{\lceil \alpha \rceil - 1} \mathbf{g}_n}{\nabla^{\lceil \alpha \rceil - 1} \mathbf{g}_{n+1}}} \nabla^{\lceil \alpha \rceil - 1} u_{n+1} - \sqrt{\frac{\nabla^{\lceil \alpha \rceil - 1} \mathbf{g}_{n+1}}{\nabla^{\lceil \alpha \rceil - 1} \mathbf{g}_n}} \nabla^{\lceil \alpha \rceil - 1} u_n = 0 \quad \text{for all } n \geq 1.$$

Because we assume $u \in \mathcal{H}_0^1$, which results in the boundary condition $u_n = 0$ for all $n \leq 0$, the above difference equation has the only solution $u_n = c \mathbf{g}_n$ for some constant $c \in \mathbb{C}$ and all $n \geq 1$. By assumption (A2.1) with $k = 0$, $\mathbf{g}_n > 0$ for all $n \geq 1$, therefore the sequence u has a compact support if and only if $c = 0$, or equivalently $u \equiv 0$. The proof of Theorem 2.10 is complete. $\square$

To complete the picture, it remains to construct an explicit parameter sequence $\mathbf{g} \in H^1$ that satisfies all the conditions (A2.1)–(A2.3). This shall be carried out in the subsequent section.

2.3 Explicit fractional Birman weights

In this section, we apply the abstract framework developed in Section 2.2 to a concrete choice of the parameter sequence $\mathbf{g}^{(\alpha)}$. In line with the leitmotif of this thesis, we define this sequence in terms of a suitable ratio of Gamma functions as

$$\mathbf{g}_n^{(\alpha)} := \frac{\Gamma(n + \alpha - 1/2)}{\Gamma(n)}, \quad \text{for all } n \in \mathbb{N}, \quad (2.23)$$

with the convention $\mathbf{g}_n^{(\alpha)} := 0$ if $n \leq 0$. This convention is necessary if $\alpha \in \mathbb{N}/2$ is a half-integer, since the Gamma function has simple poles at the points $0, -1, \dots$. This specific form is chosen because it enables an explicit closed-form computation of the action of the difference operators ∇ and $(-\Delta)^\alpha$. This property is crucial for verifying assumptions (A2.1)–(A2.3), which, in view of Theorem 2.10, imply that the sequence

$$\rho_n^{(\alpha)} := \frac{(-\Delta)^\alpha \mathbf{g}_n^{(\alpha)}}{\mathbf{g}_n^{(\alpha)}}, \quad \text{for all } n \geq 1,$$

constitutes a fractional Birman weight for every $\alpha > 0$.

Firstly, we extend the claim of Lemma 1.22 and investigate the behavior of the sequence $\mathbf{g}^{(\alpha)}$ under the action of the discrete gradient operator ∇^k . A proof can be obtained entirely analogously to that of Lemma 1.22 by invoking the Chu–Vandermonde identity for hypergeometric functions. However, we provide an alternative, more elementary argument that proceeds by induction on $k \in \{0, \dots, \lceil \alpha \rceil - 1\}$.

Lemma 2.11. *Let $\alpha > 0$ and $k \in \{0, \dots, \lceil \alpha \rceil - 1\}$. Then, for all $n \in \mathbb{Z}$, we have the identity*

$$\nabla^k \mathbf{g}_n^{(\alpha)} = (\alpha - k + 1/2)_k \mathbf{g}_n^{(\alpha-k)}. \quad (2.24)$$

Proof. It is sufficient to verify the formula for $\alpha \geq 1$ and $k = 1$. The general result then follows immediately by mathematical induction. The claim is trivial if $n \leq 0$. On the other hand, for $n \geq 1$, we obtain

$$\nabla \mathfrak{g}_n^{(\alpha)} = \frac{\Gamma(n + \alpha - 1/2)}{\Gamma(n)} - \frac{\Gamma(n + \alpha - 3/2)}{\Gamma(n - 1)} = \frac{\Gamma(n + \alpha - 1/2)}{\Gamma(n)} \left(1 - \frac{n - 1}{n + \alpha - 3/2}\right) = (\alpha - 1/2) \mathfrak{g}_n^{(\alpha-1)},$$

which coincides with the desired identity. $\square$

Remark 2.12. Note that the range of the exponent k is bounded only due to the cases where $\alpha \in \mathbb{N}/2$. Nevertheless, if $\alpha \notin \mathbb{N}/2$, the same computations yield the identity

$$\nabla^k \mathfrak{g}_n^{(\alpha)} = (\alpha - k + 1/2)_k \frac{\Gamma(n + \alpha - k - 1/2)}{\Gamma(n)}$$

for all $k \geq 0$ and $n \in \mathbb{Z}$.

Since $\mathfrak{g}_n^{(\alpha)} > 0$ for all $n \geq 1$ by the defining formula (2.23), Lemma 2.11 immediately implies the inequalities in assumption (A2.1). Furthermore, by exploiting the transition between the parameter sequences $\mathfrak{g}^{(\alpha)}$ provided by formula (2.24), we deduce that

$$\nabla^k \mathfrak{g}^{(\alpha)} \in \mathcal{D}_{\alpha-k} \quad \text{and} \quad (-\Delta)^{\alpha-k} \nabla^k \mathfrak{g}_n^{(\alpha)} > 0 \quad \text{for all } n \geq 1 \text{ and } k \in \{0, \dots, \lceil \alpha \rceil - 1\},$$

once this property has been verified for the case $k = 0$ only. Establishing this base case is the objective of the following lemma.

Lemma 2.13. *Let $\alpha > 0$. Then, for all $n \geq 1$, we have the identity*

$$(-\Delta)^\alpha \mathfrak{g}_n^{(\alpha)} = \left(\frac{1}{2}\right)_\alpha^2 \frac{\Gamma(n - 1/2)}{\Gamma(n + \alpha)}.$$

Proof. The proof will be divided into two parts, depending on whether α is an integer or not.

a) $\alpha \in \mathbb{N}$: Recalling the operator identity $\Delta = \text{div} \nabla$, for integer exponents we obtain the relation $(-\Delta)^\alpha = (-1)^\alpha \nabla^{2\alpha} \mathbb{S}^\alpha$, where the shift operator is defined in (1.8). Therefore, invoking Remark 2.12, we infer that

$$(-\Delta)^\alpha \mathfrak{g}_n^{(\alpha)} = (-1)^\alpha (-\alpha + 1/2)_{2\alpha} \frac{\Gamma(n - 1/2)}{\Gamma(n + \alpha)} = \left(\frac{1}{2}\right)_\alpha^2 \frac{\Gamma(n - 1/2)}{\Gamma(n + \alpha)}$$

for all $n \geq 1$, where the generalized Pochhammer symbol is defined by (2.5).

b) $\alpha \notin \mathbb{N}$: By definition (2.12) and the matrix representation of $(-\Delta)^\alpha$, given by Proposition 2.2, we have

$$(-\Delta)^\alpha \mathfrak{g}_n^{(\alpha)} = \sum_{m=1}^{\infty} (-1)^{m+n} \binom{2\alpha}{\alpha + m - n} \frac{\Gamma(m + \alpha - 1/2)}{\Gamma(m)}$$

for all $n \geq 1$. Recalling the definition (2.7) of the generalized binomial coefficients and shifting the index in the latter sum, we further observe that

$$(-\Delta)^\alpha \mathfrak{g}_n^{(\alpha)} = (-1)^{n+1} \Gamma(2\alpha + 1) \sum_{m=0}^{\infty} \frac{(-1)^m}{m!} \frac{\Gamma(m + \alpha + 1/2)}{\Gamma(\alpha + m - n + 2) \Gamma(\alpha - m + n)}.$$

Since $\alpha > 0$ is non-integer, the last sum can be expressed in terms of a regularized hypergeometric function as

$$\frac{\Gamma(\alpha + 1/2)}{\Gamma(\alpha + n)} \sum_{m=0}^{\infty} \frac{(\alpha + 1/2)_m (1 - \alpha - n)_m}{\Gamma(\alpha - n + 2 + m)} \frac{1}{m!} = \frac{\Gamma(\alpha + 1/2)}{\Gamma(\alpha + n)} {}_2F_1 \left(\begin{matrix} \alpha + 1/2, 1 - \alpha - n \\ \alpha - n + 2 \end{matrix} \middle| 1 \right),$$

where we used the identity

$$(-1)^m \frac{\Gamma(\alpha + n)}{\Gamma(\alpha + n - m)} = (-1)^m (\alpha + n - m)_m = (1 - \alpha - n)_m.$$

Employing also *Gauss's hypergeometric theorem* [13, Eq. (15.4.20)]

$${}_2F_1\left(\begin{matrix} a, b \\ c \end{matrix} \middle| 1\right) = \frac{\Gamma(c - a - b)}{\Gamma(c - a)\Gamma(c - b)}, \quad \text{valid whenever } \operatorname{Re}(c - a - b) > 0,$$

the expression under consideration simplifies to

$$(-\Delta)^\alpha \mathfrak{g}_n^{(\alpha)} = (-1)^{n+1} \Gamma(2\alpha + 1) \frac{\Gamma(\alpha + 1/2)}{\Gamma(\alpha + n)} \frac{\Gamma(\alpha + 1/2)}{\Gamma(3/2 - n)\Gamma(2\alpha + 1)}$$

(here the Gauss's condition reduces to $\alpha + 1/2 > 0$, which is evidently satisfied). Lastly, the Euler reflection formula (2.9) applied to $\Gamma(3/2 - n) = \Gamma(1 - (n - 1/2))$ reveals

$$(-\Delta)^\alpha \mathfrak{g}_n^{(\alpha)} = \frac{\Gamma^2(\alpha + 1/2)}{\pi} \frac{\Gamma(n - 1/2)}{\Gamma(n + \alpha)},$$

which, recalling the definition of the generalized Pochhammer symbol (2.5) coincides with the desired result. $\square$

As a consequence of Lemmas 2.11 and 2.13, we conclude that the parameter sequence $\mathfrak{g}^{(\alpha)}$ satisfies assumptions (A2.1)–(A2.3). Applying Theorem 2.10, we thus obtain the second principal result of this chapter.

Theorem 2.14. *Let $\alpha > 0$. Then the sequence*

$$\rho_n^{(\alpha)} = \frac{(-\Delta)^\alpha \mathfrak{g}_n^{(\alpha)}}{\mathfrak{g}_n^{(\alpha)}} = \left(\frac{1}{2}\right)_\alpha^2 \frac{\Gamma(n - 1/2)\Gamma(n)}{\Gamma(n - 1/2 + \alpha)\Gamma(n + \alpha)}, \quad \text{for all } n \geq 1, \quad (2.25)$$

where $\mathfrak{g}^{(\alpha)}$ is given by (2.23), is a discrete fractional Birman weight, which is non-attainable in $\mathcal{H}_0^1$.

Remark 2.15. If $\alpha = \ell \in \mathbb{N}$ is an integer, the above theorem coincides with Theorem 1.27 since

$$\rho_n^{(\ell)} = \left(\frac{1}{2}\right)_\ell^2 \frac{1}{(n - 1/2)n(n + 1/2) \cdots (n + \ell - 1)} = \rho_{n+\ell-1}^{(\ell,2)}$$

for all $n \geq 1$; see formula (1.61).

Remark 2.16. Without going into technical details, we note that, in accordance with Remark 1.29, the parameter sequences

$$\mathfrak{g}_n^{(\alpha)}(s) := \frac{\Gamma(n + \alpha - s)}{\Gamma(n)}, \quad \text{for all } n \geq 1,$$

with the convention $\mathfrak{g}_n^{(\alpha)}(s) := 0$ for $n \leq 0$, generate discrete fractional Birman weights

$$\rho_n^{(\alpha)}(s) := \frac{(-\Delta)^\alpha \mathfrak{g}_n^{(\alpha)}(s)}{\mathfrak{g}_n^{(\alpha)}(s)} = (s)_\alpha (1 - s)_\alpha \frac{\Gamma(n - s)\Gamma(n)}{\Gamma(n - s + \alpha)\Gamma(n + \alpha)}, \quad \text{for all } n \geq 1,$$

which are non-attainable in $\mathcal{H}_0^1$ for any $s \in (0, 1)$. It can be shown that the sequence $\rho_n^{(\alpha)}(s)$ attains its maximal limiting value as $n \rightarrow \infty$ at $s = 1/2$, i.e. the inequality $(s)_\alpha (1 - s)_\alpha \leq (1/2)_\alpha^2$ holds for all $s \in (0, 1)$.

To conclude this section, we establish a lower bound for the weights $\rho^{(\alpha)}$, defined in (2.25), and thereby deduce a *classical fractional Birman weight* which constitutes a direct discrete analog of the inequality (2.4).

Theorem 2.17. *Let $\alpha > 0$. Then the sequence $\rho^{(\alpha)}$, given by formula (2.25), satisfies the inequality*

$$\rho_n^{(\alpha)} > \left(\frac{1}{2}\right)_\alpha^2 \frac{1}{(n + \lceil \alpha \rceil - 1)^{2\alpha}} \quad \text{for all } n \geq 1.$$

Proof. Bearing formula (2.25) in mind, the inequality is equivalent to

$$\frac{\Gamma(n + 1/2)}{\Gamma(n + 1/2 + \alpha)} \frac{\Gamma(n + 1)}{\Gamma(n + 1 + \alpha)} > \frac{1}{(n + \lceil \alpha \rceil)^{2\alpha}} \quad \text{for all } n \geq 0,$$

which will be established once we verify that

$$\frac{\Gamma(n + s + \alpha)}{\Gamma(n + s)} \leq (n + \lceil \alpha \rceil)^\alpha \quad \text{for all } s \in [0, 1] \text{ and } n \geq 0,$$

where equality may hold only for $s = 1$. To this end, we rewrite the left-hand side as

$$\frac{\Gamma(n + s + \alpha)}{\Gamma(n + s)} = (n + s + \alpha - \lfloor \alpha \rfloor)_{\lfloor \alpha \rfloor} \frac{\Gamma(n + s + \alpha - \lfloor \alpha \rfloor)}{\Gamma(n + s)}.$$

The Pochhammer symbol is evidently estimated from above as $(n + s + \alpha - \lfloor \alpha \rfloor)_{\lfloor \alpha \rfloor} \leq (n + \lceil \alpha \rceil)^{\lfloor \alpha \rfloor}$ and the second factor satisfies

$$\frac{\Gamma(n + s + \alpha - \lfloor \alpha \rfloor)}{\Gamma(n + s)} \leq (n + s)^{\alpha - \lfloor \alpha \rfloor} \leq (n + \lceil \alpha \rceil)^{\alpha - \lfloor \alpha \rfloor},$$

as a consequence of the Gautschi inequality (1.74). Note that the latter inequality may hold as an equality only in the case $s = \lceil \alpha \rceil = 1$. Combining these two estimates yields the desired result. $\square$

Finally, we shift the index n in the fractional Birman inequality (2.16) and obtain our last main result:

Theorem 2.18 (classical fractional Birman inequality). *Let $\alpha > 0$. Then for any $u \in \mathcal{H}_0^{\lceil \alpha \rceil}$, we have the inequality*

$$\sum_{n=\lceil \alpha \rceil}^{\infty} \overline{u_n} (-\Delta)^\alpha u_n \geq \left(\frac{1}{2}\right)_\alpha^2 \sum_{n=\lceil \alpha \rceil}^{\infty} \frac{|u_n|^2}{n^{2\alpha}}. \quad (2.26)$$

Proof. It follows from Theorems 2.14 and 2.17 that

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^\alpha u_n \geq \sum_{n=1}^{\infty} \rho_n^{(\alpha)} |u_n|^2 \geq \left(\frac{1}{2}\right)_\alpha^2 \sum_{n=1}^{\infty} \frac{|u_n|^2}{(n + \lceil \alpha \rceil - 1)^{2\alpha}}$$

for all $u \in \mathcal{H}_0^1$. Moreover, the inequality is strict for every non-trivial sequence $u \neq 0$. Now consider an arbitrary sequence $u \in \mathcal{H}_0^{\lceil \alpha \rceil}$. Substituting $S^{\lceil \alpha \rceil - 1} u \in \mathcal{H}_0^1$ into the above inequality and shifting the index n in the sums on both sides yield the estimate (2.26). $\square$

2.4 Optimality of fractional Birman weights

Definition 1.1 of optimality of Hardy weights of higher order naturally extends to non-integer positive powers of the Laplace operator as follows.

Definition 2.19. The fractional Birman weight ρ is said to be optimal if it exhibits the following three properties:

- (i) *Criticality*: The weight ρ is called *critical* if for any fractional Birman weight $\tilde{\rho}$, such that $\tilde{\rho}_n \geq \rho_n$ for all $n \geq 1$, it follows that $\tilde{\rho} = \rho$.
- (ii) *Non-attainability*: The weight ρ is called *non-attainable* if, whenever the equality in (2.16) is attained for $u \in \mathcal{D}_\alpha$ such that the right-hand side is finite, necessarily $u \equiv 0$.
- (iii) *Optimality near infinity*: The weight ρ is called *optimal near infinity* if for any $M \geq 1$ and $\varepsilon > 0$ there exists $u \in \mathcal{H}_0^M$ such that

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^\alpha u_n < (1 + \varepsilon) \sum_{n=1}^{\infty} \rho_n |u_n|^2.$$

Note that for non-attainability, we restrict our attention only to the sequences in the domain $\mathcal{D}_\alpha$, for which the left-hand side of the fractional Birman inequality is well-defined.

In this section, we discuss the optimality properties of the fractional Birman weights $\rho^{(\alpha)}$ derived in Theorem 2.14. The overall strategy is analogous to that employed in Chapter 1, where the optimality of abstract p -Birman weights was established in Theorem 1.10. In close parallel to the proof of Theorem 1.10 in Section 1.2.1.4, the key idea is that all remainder terms on the right-hand side of identity (2.19) vanish under the formal substitution $u = \mathbf{g}$, i.e.

$$R_k^{(\alpha)}(\mathbf{g}, \mathbf{g}) = 0 \quad \text{for all } \alpha > 0 \text{ and } k \in \{1, \dots, \lceil \alpha \rceil\};$$

see definition (2.20). Once again, we cannot perform the substitution $u = \mathbf{g}$ directly, since the parameter sequence $\mathbf{g}$ is not compactly supported. Therefore, it is necessary to analyze the asymptotic behavior of the remainder terms as $u^N \rightarrow \mathbf{g}$. However, several technical difficulties, detailed in Remarks 2.25 and 2.28, arise in the fractional setting, which prevent us from establishing the optimality of the weights $\rho^{(\alpha)}$ in full generality. Nevertheless, we anticipate that the following conjecture holds. In fact, partial results supporting this statement will be progressively proven in the remainder of this section.

Conjecture 2.20. *Let $\alpha > 0$. Then the fractional Birman weights*

$$\rho_n^{(\alpha)} = \left(\frac{1}{2}\right)_\alpha^2 \frac{\Gamma(n - 1/2)\Gamma(n)}{\Gamma(n - 1/2 + \alpha)\Gamma(n + \alpha)}, \quad \text{for all } n \geq 1,$$

are optimal in the sense of Definition 2.19.

Remark 2.21. Recalling the asymptotic expansion (1.59), we observe that

$$\rho_n^{(\alpha)} \sim \left(\frac{1}{2}\right)_\alpha^2 \frac{1}{n^{2\alpha}}, \quad \text{as } n \rightarrow \infty.$$

Consequently, validity of Conjecture 2.20, or, in particular, of optimality near infinity of the weights $\rho^{(\alpha)}$, would also imply the optimality of the *fractional Birman constant*

$$B^{(\alpha)} := \left(\frac{1}{2}\right)_\alpha^2$$

on the right-hand side of the classical fractional Birman inequality (2.26) for all $\alpha > 0$.

Remark 2.22. The conjecture is obviously true for integer parameters $\alpha \in \mathbb{N}$, since it coincides with Theorem 1.27 in the particular case $p = 2$.

We now proceed to analyze individually the three properties that characterize optimality, namely criticality, non-attainability, and optimality near infinity:

Criticality

Similarly to the argument presented in Section 1.2.1.4, the criticality is established by showing that the remainder terms $R_k^{(\alpha)}(\mathbf{g}, \mathbf{g}\xi^N)$, where ξ^N denotes a suitable cut-off function, vanish as $N \rightarrow \infty$ for every $k \in \{1, \dots, \lceil \alpha \rceil\}$. In what follows, we confine our attention to the setting of fractional Hardy inequalities, i.e. to the case $\alpha \in (0, 1)$, where the analysis simplifies substantially due to the presence of only a single remainder term. Within this range of the parameter α , we derive an even stronger result, reminiscent of Theorem 1.10.

Proposition 2.23. *Let $\alpha \in (0, 1)$. Suppose that $\mathbf{g} \in H^1$ satisfies the assumptions (A2.1) and (A2.3) (assumption (A2.2) is void), and, in addition, suppose that $\mathbf{g}$ admits the asymptotic expansion*

$$\mathbf{g}_n = c n^{\alpha-1/2} + \mathcal{O}(n^{\alpha-3/2}), \quad \text{as } n \rightarrow \infty, \text{ where } c \neq 0. \quad (\text{A2.4})$$

Then the fractional Hardy weight $\rho(\mathbf{g}) = (-\Delta)^\alpha \mathbf{g}/\mathbf{g}$ is critical.

Proof. Consider a fractional Hardy weight $\tilde{\rho}$ such that $\tilde{\rho}_n \geq \rho_n(\mathbf{g})$ for all $n \geq 1$. By assumption (A2.1), the weight $\rho(\mathbf{g})$ satisfies the identity (2.19), thus the fractional Hardy inequality for $\tilde{\rho}$ implies that

$$0 \leq \sum_{n=1}^{\infty} (\tilde{\rho}_n - \rho_n(\mathbf{g})) |u_n|^2 \leq R_1^{(\alpha)}(\mathbf{g}, u)$$

for all $u \in \mathcal{H}_0^1$. We will use these inequalities for a regularization of the parameter sequence $\mathbf{g}$ of the form $u^N := \mathbf{g}\xi^N$, where, this time, the cut-off sequences ξ^N are defined as

$$\xi_n^N := \begin{cases} 1 & \text{if } n \leq N, \\ \frac{2 \ln N - \ln n}{\ln N} & \text{if } N < n \leq N^2, \\ 0 & \text{if } n > N^2, \end{cases} \quad (2.27)$$

for any $N \geq 2$. Notice that $\xi^N \rightarrow 1$, and therefore $u^N \rightarrow \mathbf{g}$, point-wise, as $N \rightarrow \infty$. Moreover, we will show that the remainder admits the estimate

$$R_1^{(\alpha)}(\mathbf{g}, u^N) \lesssim \frac{1}{\log N} \quad \text{for any } N \geq 2, \quad (2.28)$$

where $\lesssim$ denotes the inequality $\leq$ up to a N -independent constant. Hence, invoking Fatou's lemma, we find that

$$\sum_{n=1}^{\infty} (\tilde{\rho}_n - \rho_n(\mathbf{g})) \mathbf{g}_n^2 = \sum_{n=1}^{\infty} (\tilde{\rho}_n - \rho_n(\mathbf{g})) \lim_{N \rightarrow \infty} |u_n^N|^2 \leq \liminf_{N \rightarrow \infty} \sum_{n=1}^{\infty} (\tilde{\rho}_n - \rho_n(\mathbf{g})) |u_n^N|^2 = 0.$$

From the non-negativity of the summands on the left and positivity of $\mathbf{g}_n$ for all $n \geq 1$, ensured by assumption (A2.1), we conclude that $\tilde{\rho}_n = \rho_n(\mathbf{g})$ for all $n \geq 1$, which proves the criticality of the weight $\rho(\mathbf{g})$.

It remains to verify the estimate (2.28). Substituting $u := u^N = \mathbf{g}\xi^N$ into the defining formula (2.20) reveals

$$R_1^{(\alpha)}(\mathbf{g}, u^N) = \sum_{n=1}^{\infty} \sum_{j=1}^{\infty} -(-\Delta)_{n+j,n}^\alpha \mathbf{g}_{n+j} \mathbf{g}_n |\xi_{n+j}^N - \xi_n^N|^2.$$

Recalling definition (2.27), one readily confirms that

$$|\xi_{n+j}^N - \xi_n^N| \leq \frac{\log(1+j/n)}{\log N} \quad \text{for all } n, j \geq 1. \quad (2.29)$$

Next, we employ the estimate (2.13) for the matrix elements of $(-\Delta)^\alpha$, as well as the assumption (A2.4), to obtain

$$\begin{aligned} R_1^{(\alpha)}(\mathbf{g}, u^N) &\lesssim \sum_{n=1}^{N^2} \sum_{j=1}^{\infty} \frac{1}{j^{2\alpha+1}} n^{\alpha-1/2} (n+j)^{\alpha-1/2} \frac{\log^2(1+j/n)}{\log^2 N} \\ &= \frac{1}{\log^2 N} \sum_{n=1}^{N^2} \frac{1}{n^2} \sum_{j=1}^{\infty} \frac{(1+j/n)^{\alpha-1/2}}{(j/n)^{2\alpha+1}} \log^2(1+j/n). \end{aligned}$$

Moreover, for any $n \geq 1$ fixed, the function

$$(0, \infty) \rightarrow (0, \infty) : x \mapsto \frac{(1+x/n)^{\alpha-1/2}}{(x/n)^{2\alpha+1}} \log^2(1+x/n)$$

is eventually decreasing, thus the inner sum can be further estimated by the integral

$$\sum_{j=1}^{\infty} \frac{(1+j/n)^{\alpha-1/2}}{(j/n)^{2\alpha+1}} \log^2(1+j/n) \lesssim \int_0^{\infty} \frac{(1+x/n)^{\alpha-1/2}}{(x/n)^{2\alpha+1}} \log^2(1+x/n) dx.$$

Finally, using the substitution $t = x/n$, we infer that

$$R_1^{(\alpha)}(\mathbf{g}, u^N) \lesssim \frac{1}{\log^2 N} \sum_{n=1}^{N^2} \frac{1}{n} \left(\int_0^{\infty} \frac{(1+t)^{\alpha-1/2}}{t^{2\alpha+1}} \log^2(1+t) dt \right) \lesssim \frac{1}{\log^2 N} \int_0^{N^2} \frac{1}{n} dn \lesssim \frac{1}{\log N},$$

where the integral in parentheses converges to some positive constant since $\alpha \in (0, 1)$. The proof of the estimate (2.28), and therefore of Proposition 2.23 is complete. $\square$

Remark 2.24. In view of expansion (1.59), the parameter sequences $\mathbf{g}^{(\alpha)}$, defined by (2.23), satisfy the assumption (A2.4), and therefore the above proposition evidently implies criticality of the fractional Hardy weights $\rho^{(\alpha)}$ for any $\alpha \in (0, 1)$.

Remark 2.25. There are two principal obstacles to extending Proposition 2.23 to the entire range $\alpha > 0$:

- Firstly, we are currently unable to determine estimates

$$\frac{(-\Delta)^{\alpha-k} \nabla^k \mathbf{g}_n}{\nabla^k \mathbf{g}_n} \lesssim n^{2(k-\alpha)}$$

of the prefactors of the summands in the remainder terms (2.20), for $k \in \{1, \dots, \lceil \alpha \rceil - 1\}$, under the additional assumption (A2.4) (or even a stronger assumption imposed on the asymptotic behavior of $\mathbf{g}_n$, as $n \rightarrow \infty$). Fortunately, this difficulty can be circumvented through a suitable explicit choice of the parameter sequence $\mathbf{g}^{(\alpha)}$. Indeed, by invoking Lemmas 2.11 and 2.13, we obtain

$$\frac{(-\Delta)^{\alpha-k} \nabla^k \mathbf{g}_n^{(\alpha)}}{\nabla^k \mathbf{g}_n^{(\alpha)}} = \rho_n^{(\alpha-k)} \sim \left(\frac{1}{2}\right)_{\alpha-k}^2 \frac{1}{n^{2(\alpha-k)}}, \quad \text{as } n \rightarrow \infty.$$

- Second, the bounds of the remainder terms, for $k \in \{1, \dots, \lceil \alpha \rceil - 1\}$, of the form

$$R_k^{(\alpha)}(\mathbf{g}^{(\alpha)}, \mathbf{g}^{(\alpha)} \xi^N) \lesssim \frac{1}{\log N}, \quad \text{for all } N \geq 2,$$

where the regularization ξ^N is defined in (1.34), can be derived by employing an argument analogous to that used in Section 1.2.1.4. In contrast, if $k = \lceil \alpha \rceil$, the double summation in formula (2.20) renders the analysis significantly more intricate, which prevents us from establishing the corresponding estimate.

Optimality near infinity

The proof of optimality near infinity proceeds along the same lines as the argument given in Section 1.2.1.4. As before, we confine our attention to the Hardy regime $\alpha \in (0, 1)$. The motivation for this restriction is similar to the reasons listed in Remark 2.25.

Proposition 2.26. *Let $\alpha \in (0, 1)$. Then the fractional Hardy weight $\rho^{(\alpha)}$, given by formula (2.25), is optimal near infinity.*

Proof. Fix arbitrary $M \geq 1$. Recalling identity (2.19), the optimality near infinity will be established once we find a sequence $\{u^N\}_{N \geq M} \subset \mathcal{H}_0^M$ such that

$$\lim_{N \rightarrow \infty} \frac{R_1^{(\alpha)}(\mathfrak{g}^{(\alpha)}, u^N)}{\sum_{n=1}^{\infty} \rho_n^{(\alpha)} |u_n^N|^2} = 0. \quad (2.30)$$

This time, we set $u^N := \mathfrak{g}^{(\alpha)} \xi^N$, where ξ^N is a *bump sequence* determined by

$$\xi_n^N := \begin{cases} 0 & \text{if } n \leq N, \\ \frac{\log n - \log N}{\log N} & \text{if } N < n \leq N^2, \\ 1 & \text{if } N^2 < n \leq 2N^2, \\ \frac{\log(2N^3) - \log n}{\log N} & \text{if } 2N^2 < n \leq 2N^3, \\ 0 & \text{if } n > 2N^3, \end{cases}$$

for all $N \geq M$. It is straightforward to check that the inequality (2.29) still holds, hence, similarly as in the proof of criticality, we find that

$$R_1^{(\alpha)}(\mathfrak{g}^{(\alpha)}, \mathfrak{g}^{(\alpha)} \xi^N) \lesssim \frac{1}{\log^2 N} \sum_{n=1}^{2N^3} \frac{1}{n} \lesssim \frac{1}{\log N} \rightarrow 0, \quad \text{as } N \rightarrow \infty.$$

On the other hand, the asymptotic expansion (1.59) implies the lower bounds

$$\rho_n^{(\alpha)} = \left(\frac{1}{2}\right)_\alpha^2 \frac{\Gamma(n-1/2)\Gamma(n)}{\Gamma(n-1/2+\alpha)\Gamma(n+\alpha)} \gtrsim \frac{1}{n^{2\alpha}} \quad \text{and} \quad \mathfrak{g}_n^{(\alpha)} = \frac{\Gamma(n+\alpha-1/2)}{\Gamma(n)} \gtrsim n^{\alpha-1/2}, \quad (2.31)$$

for all $n \geq 1$, and therefore the denominator of the expression in (2.30) satisfies

$$\sum_{n=1}^{\infty} \rho_n^{(\alpha)} |u_n^N|^2 \geq \sum_{n=N^2}^{2N^2} \rho_n^{(\alpha)} (\mathfrak{g}_n^{(\alpha)})^2 \gtrsim \sum_{n=N^2}^{2N^2} \frac{n^{2\alpha-1}}{n^{2\alpha}} \geq \int_{N^2}^{2N^2} \frac{1}{n} dn = \log 2.$$

Altogether, we verify (2.30), and hence also the optimality near infinity of the weight $\rho^{(\alpha)}$. $\square$

Non-attainability

We shall establish an intermediate non-attainability property that lies between the notion of non-attainability introduced in Definition 2.19 and the notion of non-attainability in $\mathcal{H}_0^1$ given in Definition 2.6. By approximating sequences in $\mathcal{H}^{1,2} \subset \mathcal{D}_\alpha$ (see definition (1.6)) with compactly supported sequences, we extend the results of Theorem 2.14 and demonstrate that the fractional Birman weight $\rho^{(\alpha)}$ remains *non-attainable* even in the space $\mathcal{H}^{1,2}$, for any $\alpha > 0$. Recall that a fractional Birman weight ρ is said to be *non-attainable* in $\mathcal{H}^{1,2}$ if, whenever equality in (2.16) is attained for $u \in \mathcal{H}^{1,2}$, necessarily $u \equiv 0$.

Proposition 2.27. *Let $\alpha > 0$. Then the fractional Birman weight $\rho^{(\alpha)}$, given by formula (2.25), is non-attainable in $\mathcal{H}^{1,2}$.*

Proof. The proof proceeds analogously to the argument outlined in Section 1.2.1.4. Suppose that $u \in \mathcal{H}^{1,2}$ satisfies the equality

$$\sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^{\alpha} u_n = \sum_{n=1}^{\infty} \rho_n^{(\alpha)} |u_n|^2.$$

Consider a sequence $\{u^N\}_{N=1}^{\infty} \subset \mathcal{H}_0^1$ of compactly supported sequences approximating u , i.e. $u^N \rightarrow u$ as $N \rightarrow \infty$ in the norm of $\ell^2(\mathbb{Z})$. Theorem 2.9 implies the identity

$$0 \leq \sum_{k=1}^{\lceil \alpha \rceil} R_k^{(\alpha)}(\mathfrak{g}, u^N) = \sum_{n=1}^{\infty} \overline{u_n^N} (-\Delta)^{\alpha} u_n^N - \sum_{n=1}^{\infty} \rho_n^{(\alpha)} |u_n^N|^2$$

for all $N \geq 1$. Since both $(-\Delta)^{\alpha}$ and $\rho^{(\alpha)}$ determine bounded operators on $\ell^2(\mathbb{Z})$, in fact

$$\|(-\Delta)^{\alpha}\| = 4^{\alpha} \quad \text{and} \quad \|\rho^{(\alpha)}\| = \sup_{n \geq 1} |\rho_n^{(\alpha)}| = \frac{\Gamma(\alpha + 1/2)}{\sqrt{\pi} \Gamma(\alpha + 1)},$$

passing to the limit $N \rightarrow \infty$ in the identity above shows that the remainders converge to zero as $N \rightarrow \infty$ for any $k \in \{1, \dots, \lceil \alpha \rceil\}$.

Proceeding verbatim as in the proof of Theorem 2.10, we deduce that $u_n = c \mathfrak{g}_n^{(\alpha)}$ for some complex constant $c \in \mathbb{C}$. Furthermore, if $c \neq 0$, the estimates in (2.31) entail

$$\sum_{n=1}^{\infty} \rho_n^{(\alpha)} |u_n|^2 \gtrsim \sum_{n=1}^{\infty} \frac{1}{n^{2\alpha}} n^{2\alpha-1} = \infty.$$

Finally, recalling the assumption $u \in \mathcal{H}^{1,2}$ (hence also $\sqrt{\rho^{(\alpha)}} u \in \mathcal{H}^{1,2}$), we conclude that $c = 0$, i.e. $u \equiv 0$. The proof of Proposition 2.27 is complete. $\square$

Remark 2.28. The sole remaining ingredient required to extend the statement of Proposition 2.27 to the notion of non-attainability (in $\mathcal{D}_{\alpha}$), as introduced in Definition 2.19, is the establishment of an approximation result analogous to Lemma 1.17. Namely, one needs to establish the existence of a sequence $\{u^N\}_{N=1}^{\infty} \subset \mathcal{H}_0^1$ such that

$$\sum_{n=1}^{\infty} \overline{u_n^N} (-\Delta)^{\alpha} u_n^N \xrightarrow{N \rightarrow \infty} \sum_{n=1}^{\infty} \overline{u_n} (-\Delta)^{\alpha} u_n,$$

provided that $u \in \mathcal{D}_{\alpha}$ and that the series on the right-hand side converges.

Conclusion

In this thesis, we conducted a detailed analysis of optimal higher-order discrete Hardy inequalities on the half-line. Our investigation focused on two contemporary research directions: nonlinear p -Hardy inequalities and extensions of Hardy-type inequalities in the linear case $p = 2$ to non-integer positive powers of the discrete Laplace operator.

In Chapter 1, we developed a general framework for discrete p -Hardy inequalities of arbitrary order $\ell \in \mathbb{N}$ and exponent $p > 1$. Starting from an abstract first-order weighted inequality, we established an iterative method that enables the construction of higher-order p -Hardy weights from a suitable parameter sequence. In this way, we identified sufficient conditions under which these weights are optimal, i.e. critical, non-attainable, and optimal near infinity, in Theorem 1.10. This approach led to the discovery of explicit optimal discrete p -Birman weights $\rho^{(\ell,p)}$ in Theorem 1.27, extending our previous results from [43], where only the linear case $p = 2$ was considered. Moreover, subsequent analysis of the optimal weights $\rho^{(\ell,p)}$ yielded the classical discrete (Theorem 1.38) and continuous (Theorem 1.46) p -Birman inequalities, which, to the best of our knowledge, have not been explicitly formulated in the existing literature.

In Chapter 2, we turned to the linear case $p = 2$ and extended the theory to fractional powers of the discrete Laplacian. In contrast to previous works [18, 11], we studied the Toeplitz operator $(-\Delta)^\alpha$ for arbitrary $\alpha > 0$, defined as a restriction of the full-line discrete Laplacian in Section 2.1. In this setting, we established fractional Birman inequalities depending on a parameter sequence $\mathbf{g}$ in Theorem 2.10. By a suitable explicit choice of $\mathbf{g}^{(\alpha)}$, we derived corresponding fractional Birman weights $\rho^{(\alpha)}$ in Theorem 2.14, as well as the classical fractional Birman inequality in Theorem 2.18.

Several open problems remain for future research. In particular, we highlight the alternative candidates for optimal p -Birman weights $\tilde{\rho}^{(\ell,p)}$ and the question of optimality of the fractional Birman weights $\rho^{(\alpha)}$. These problems are formulated in Conjectures 1.36 and 2.20 respectively, and are supported by partial results established in special cases. Further directions may also include extensions of fractional Birman inequalities beyond the linear case $p = 2$ or analogous results in an abstract graph setting.

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