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Distributional representations of $\mathcal{N}_\kappa^{(\infty)}$ -functions

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Abstract

The subclasses $\mathcal{N}_\kappa^{(\infty)}$ of the classes \mathcal{N}_κ of generalized Nevanlinna functions appear in the context of Pontryagin space models, where they correspond to model relations having a particular spectral behaviour. Applications are found, for instance, in the investigation of differential expressions with singular coefficients. We study representations of $\mathcal{N}_\kappa^{(\infty)}$ -functions as Cauchy-type integrals in a distributional sense and characterize the class of distributions occurring in such representations. We make explicit how the Pontryagin space model of an $\mathcal{N}_\kappa^{(\infty)}$ -function is related to the multiplication operator in the L^2 -space of the measure which describes the action of the representing distribution away from infinity. Moreover, we determine the distributional representations of a pair of functions associated with a symmetric generalized Nevanlinna function.

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1 Introduction

A function q is said to belong to the *Nevanlinna class* \mathcal{N}_0 if it is analytic in $\mathbb{C} \setminus \mathbb{R}$, satisfies $q(\bar{z}) = \overline{q(z)}$, $z \in \mathbb{C} \setminus \mathbb{R}$, and

$$\operatorname{Im} q(z) \cdot \operatorname{Im} z \geq 0, \quad z \in \mathbb{C} \setminus \mathbb{R}.$$

This class of functions has been intensively studied in various contexts of analysis. For instance, it plays an important role in the spectral theory of symmetric and self-adjoint operators in a Hilbert space or in classical problems like the power moment problem.

A fact which lies at the very core of the subject is that a function $q \in \mathcal{N}_0$ can be represented as a Cauchy-type integral. This result goes back to the early stages of modern analysis; it is commonly attributed to the work of G. Herglotz from the 1910s.

1.1. Herglotz integral representation. *A function q belongs to the Nevanlinna class \mathcal{N}_0 if and only if it can be represented as*

$$q(z) = a + bz + \int_{\mathbb{R}} \left(\frac{1}{t-z} - \frac{t}{1+t^2} \right) d\mu(t), \quad z \in \mathbb{C} \setminus \mathbb{R}, \quad (1.1)$$

where $a \in \mathbb{R}$, $b \geq 0$, and μ is a positive Borel measure on the real line with

$$\int_{\mathbb{R}} \frac{d\mu(t)}{1+t^2} < \infty.$$

In many applications to differential operators the measure μ plays the role of a spectral measure.

In the theory of spaces with an indefinite metric, in particular in the spectral theory of symmetric and self-adjoint operators in a Pontryagin space, an indefinite analogue of the class \mathcal{N}_0 occurs.

1.2 Definition. A function q is said to belong to the *generalized Nevanlinna class* $\mathcal{N}_{<\infty}$ if it is meromorphic in $\mathbb{C} \setminus \mathbb{R}$, satisfies $q(\bar{z}) = \overline{q(z)}$, $z \in \rho(q)$ (where $\rho(q)$ denotes the domain of analyticity of q), and the kernel

$$K_q(w, z) := \frac{q(z) - \overline{q(w)}}{z - \bar{w}}, \quad z, w \in \rho(q),$$

has a finite number of negative squares. By this we mean that the numbers of negative squares of the quadratic forms

$$Q(\xi_1, \dots, \xi_n) := \sum_{i,j=1}^n K_q(z_j, z_i) \xi_i \bar{\xi}_j,$$

where $n \in \mathbb{N}$ and $z_1, \dots, z_n \in \rho(q)$, is bounded independently of n and z_1, \dots, z_n .

If $q \in \mathcal{N}_\infty$, we denote by $\text{ind}_- q$ the actual number of negative squares of K_q that is, the maximum of the numbers of negative squares of forms $Q(\xi_1, \dots, \xi_n)$, $n \in \mathbb{N}$, $z_1, \dots, z_n \in \rho(q)$. Moreover, set

$$\mathcal{N}_\kappa := \{q \in \mathcal{N}_{<\infty} : \text{ind}_- q = \kappa\}.$$

◇

A systematic study of the class $\mathcal{N}_{<\infty}$ was given by M. G. Kreĭn and H. Langer in [31]. Over the years a vast literature accumulated, dealing in particular with Kreĭn's resolvent formula, boundary triples and Weyl functions, or analytic properties and operator representations. To mention just a few out of the recent literature, we refer to [1, 2, 3, 4, 6, 7, 9, 21, 28].

A central result is the integral representation of generalized Nevanlinna functions given in [31, Satz 3.1], which is the indefinite analogue of the Herglotz integral representation. Using the work [24] on distributional models for cyclic self-adjoint operators in a Pontryagin space, one obtains a distributional form of this integral representation. This fact is mentioned in [24, Introduction, p. 253], established in full generality in [27, Corollary 3.5] and refined in [25, Proposition 5.4].

In various contexts, in particular in connection with spectral properties of operator models for differential operators, subclasses of \mathcal{N}_0 and their indefinite analogues occur, for instance, the Kac subclasses, see, e.g. [7], or the Stieltjes class, see, e.g. [26].

A class that is specific to the indefinite situation is the class $\mathcal{N}_{<\infty}^{(\infty)}$ (which is sometimes denoted by $\mathcal{N}_{<\infty}^\infty$ in the literature). Functions in this class are characterized by, in a certain sense, maximal possible growth at infinity; we recall its precise definition in Definition 3.5 below. It occurs in the spectral theory of Sturm–Liouville differential operators with singular coefficients, see [8, 11, 15, 17, 18, 30, 35]. Operator models from an abstract point of view were studied [10, 12, 13, 14].

This class $\mathcal{N}_{<\infty}^{(\infty)}$ lies in the focus of our present study. Our aim is to investigate distributional representations of functions in this class, continuing the line of research from [24], [27, Corollary 3.5], [25, Proposition 5.4]. The main results in the present paper are

1. Theorem 3.9, where we characterize those distributions appearing in representations of $\mathcal{N}_{<\infty}^{(\infty)}$ -functions;
2. Theorem 4.4, where we determine the representing distributions of functions q_+ and q_- naturally associated with a symmetric generalized Nevanlinna function, paying particular attention to the case when $q \in \mathcal{N}_{<\infty}^{(\infty)}$;
3. Theorem 5.3, where we make explicit the connection between the “measure part” of the representing distribution, the algebraic eigenspace at ∞ of the corresponding self-adjoint relation (for which ∞ is in general a singular critical point), and the multiplication operator in a certain L^2 -space.

Besides their intrinsic interest, these results are an essential tool for our forthcoming work on direct and inverse spectral theorems for two-dimensional canonical systems and Sturm–Liouville equations with two singular endpoints. These theorems will be presented in [36], and they rely heavily on the present results.

Let us briefly outline the organization of the manuscript. In Section 2 we undertake a systematic study of the class $\mathcal{F}_{\{\infty\}}$ of distributional densities on $\overline{\mathbb{R}}$. We include this material to provide the reader with a polished form of the analytic setup and the representation theorem itself, which cannot be found elsewhere. In the following three sections we formulate and prove our main results. Thereby Section 3 is devoted to the actual representations of $\mathcal{N}_{<\infty}^{(\infty)}$ -functions, in Section 4 we investigate the symmetric case, and in Section 5 we turn to the operator-theoretic aspects.

We aim to keep proofs as elementary as possible. This is not always the most efficient approach. However, we believe that clearly isolating what has to be imported and being detailed in what has to be done is for the benefit of the reader, and hence find it worth to proceed in this way¹. We add some more detailed notices on alternative ways of proof in the course of the exposition.

2 The class $\mathcal{F}_{\{\infty\}}$ of distributional densities

When Ω is an open subset of \mathbb{R}^n , the space of test functions, $\mathcal{D}(\Omega)$, and its dual, the space of distributions $\mathcal{D}'(\Omega)$, are studied in many textbooks. We refer, for example, to [5], [16] or [22], and take this theory for granted. The notion of distributions and distributional densities on a manifold seems to be much less standard. Our reference is the classic book [23]; an intrinsic geometric approach can be found in [20].

The manifold that appears in the context of representations of generalized Nevanlinna functions is $\overline{\mathbb{R}} := \mathbb{R} \cup \{\infty\}$, the one-point compactification of \mathbb{R} . We consider $\overline{\mathbb{R}}$ as a C^∞ -manifold in the usual way via the charts (here, and in the

¹In this context, we should mention that in the earlier literature on the subject proofs are often not carried out in detail.

following, we understand $\frac{1}{\infty} := 0$ and $\frac{1}{0} := \infty$)

$$\Lambda_0 : \begin{cases} \overline{\mathbb{R}} \setminus \{\infty\} & \rightarrow \mathbb{R}, \\ x & \mapsto x, \end{cases} \quad \Lambda_\infty : \begin{cases} \overline{\mathbb{R}} \setminus \{0\} & \rightarrow \mathbb{R}, \\ x & \mapsto \frac{1}{x}. \end{cases}$$

We want to emphasize the viewpoint of linear functionals and hence work with distributional densities rather than distributions. Let us recall the definition from [23, p. 145] (we formulate it only for the particular manifold $\overline{\mathbb{R}}$ using the particular charts Λ_0 and Λ_∞).

2.1 Definition. A *distributional density* ϕ on $\overline{\mathbb{R}}$ is a pair (ϕ_0, ϕ_∞) where ϕ_0 and ϕ_∞ belong to $\mathcal{D}'(\mathbb{R})$ and are related by the transformation law²

$$\phi_\infty(f) = \phi_0(f \circ (\Lambda_\infty \circ \Lambda_0^{-1})), \quad f \in \mathcal{D}(\mathbb{R}), \quad 0 \notin \text{supp } f. \quad (2.1)$$

We denote the set of all distributional densities on $\overline{\mathbb{R}}$ by $\widetilde{\mathcal{D}}'(\overline{\mathbb{R}})$. \diamond

Throughout this paper, we drop the explicit notation of Λ_0 and consider the auxiliary Euclidean space \mathbb{R} as a subset of the manifold $\overline{\mathbb{R}}$.

Each distributional density ϕ induces a linear functional on $C^\infty(\overline{\mathbb{R}})$ in a canonical way: choose a partition of unity $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ subordinate to the open cover $\{\overline{\mathbb{R}} \setminus \{\infty\}, \overline{\mathbb{R}} \setminus \{0\}\}$ of $\overline{\mathbb{R}}$, and define

$$\phi(g) := \phi_0(\chi^0 g) + \phi_\infty((\chi^\infty g) \circ \Lambda_\infty^{-1}), \quad g \in C^\infty(\overline{\mathbb{R}}). \quad (2.2)$$

Due to the transformation law (2.1), this definition is independent of the choice of χ^0, χ^∞ .

2.2 Remark. Let $\phi = (\phi_0, \phi_\infty) \in \widetilde{\mathcal{D}}'(\overline{\mathbb{R}})$. It is another consequence of the transformation law (2.1) that both distributions ϕ_0 and ϕ_∞ have finite order. To see this, choose $N_0, N_\infty \in \mathbb{N}_0$ and $C_0, C_\infty > 0$ such that

$$\begin{aligned} |\phi_0(f)| &\leq C_0 \|f\|_{[-2,2],N_0}, \quad f \in \mathcal{D}(\mathbb{R}), \quad \text{supp } f \subseteq [-2,2], \\ |\phi_\infty(f)| &\leq C_\infty \|f\|_{[-1,1],N_\infty}, \quad f \in \mathcal{D}(\mathbb{R}), \quad \text{supp } f \subseteq [-1,1]; \end{aligned}$$

here, for a compact subset K of \mathbb{R} and $n \in \mathbb{N}_0$, we set

$$\|f\|_{K,n} := \max \left\{ \sup_{x \in K} |f^{(k)}(x)| : k = 0, \dots, n \right\}, \quad f \in \mathcal{D}(\mathbb{R}).$$

Choose a partition of unity $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ subordinate to the open cover $\{(-2,2), \overline{\mathbb{R}} \setminus [-1,1]\}$ of $\overline{\mathbb{R}}$, and set $N := \max\{N_0, N_\infty\}$. Then, for each $T \geq 2$, we find a constant $C_T > 0$ such that, for $f \in \mathcal{D}(\mathbb{R})$ with $\text{supp } f \subseteq [-T, T]$,

$$\begin{aligned} |\phi_0(f)| &\leq |\phi_0(\chi^0 f)| + |\phi_\infty((\chi^\infty f) \circ \Lambda_\infty^{-1})| \\ &\leq C_0 \|\chi^0 f\|_{[-2,2],N_0} + C_\infty \|(\chi^\infty f) \circ \Lambda_\infty^{-1}\|_{[-1,1],N_\infty} \leq C_T \|f\|_{[-T,T],N}. \end{aligned}$$

The dependence on T arises from the derivatives of the map Λ_∞ . In any case, this estimate shows that $\text{ord } \phi_0 \leq N$. The fact that $\text{ord } \phi_\infty \leq N$ is seen in the same way. \diamond

²On comparing (2.1) with the requirement [23, (6.3.4)], one may wonder why the factor “ $|\det \psi'|$ ” disappeared. In fact, it did not. This is due to the definition of “ f^* ” in [23]; the example [23, 6.1.3] may be enlightening.

Let us introduce the *order* of a distributional density:

$$\text{ord } \phi := \max\{\text{ord } \phi_0, \text{ord } \phi_\infty\}, \quad \phi = (\phi_0, \phi_\infty) \in \widetilde{\mathcal{D}}'(\overline{\mathbb{R}}).$$

In connection with generalized Nevanlinna functions, a subset $\mathcal{F}(\overline{\mathbb{R}})$ of $\widetilde{\mathcal{D}}'(\overline{\mathbb{R}})$ appears, which is defined in Definition 2.3 (iii) below. Thereby, we call a distribution $\phi \in \mathcal{D}'(\mathbb{R})$ *real* if it assigns real values to real-valued test functions.

2.3 Definition.

- (i) Let $\phi \in \mathcal{D}'(\mathbb{R})$ and let $M \subseteq \mathbb{R}$ be an open set. Then we say that ϕ is a *positive measure on M* if there exists a positive (possibly unbounded) Borel measure μ on M such that

$$\phi(f) = \int_M f \, d\mu \quad \text{for all } f \in \mathcal{D}(\mathbb{R}) \text{ with } \text{supp } f \subseteq M.$$

Here, and in the rest of the paper, we include in the notion of a Borel measure the requirement that compact sets have finite measure.

- (ii) Let $\phi = (\phi_0, \phi_\infty) \in \widetilde{\mathcal{D}}'(\overline{\mathbb{R}})$ and let $M \subseteq \overline{\mathbb{R}}$ be an open set. We say that ϕ is a *positive measure on M* if ϕ_0 is a positive measure on $M \cap \mathbb{R}$ and ϕ_∞ is a positive measure on $\Lambda_\infty(M \setminus \{0\})$.
- (iii) Let $\phi = (\phi_0, \phi_\infty) \in \widetilde{\mathcal{D}}'(\overline{\mathbb{R}})$. We say that ϕ belongs to $\mathcal{F}(\overline{\mathbb{R}})$ if ϕ_0 and ϕ_∞ are real and there exists a finite subset $F \subseteq \overline{\mathbb{R}}$ such that ϕ is a positive measure on $\overline{\mathbb{R}} \setminus F$.
- (iv) If $\phi \in \mathcal{F}(\overline{\mathbb{R}})$, we denote by $s(\phi)$ the smallest of all sets F such that ϕ is a positive measure on $\overline{\mathbb{R}} \setminus F$. ◇

To justify item (iv) of this definition, note that ϕ being a positive measure on $\overline{\mathbb{R}} \setminus F_1$ and $\overline{\mathbb{R}} \setminus F_2$ implies that ϕ is a positive measure on $\overline{\mathbb{R}} \setminus (F_1 \cap F_2)$. Moreover, note that a measure μ as in (i) is uniquely determined by ϕ .

The subclass $\mathcal{F}_{\{\infty\}}$ of $\mathcal{F}(\overline{\mathbb{R}})$, which is defined below, is one of the central objects in our present study.

2.4 Definition. We denote by $\mathcal{F}_{\{\infty\}}$ the set of all $\phi = (\phi_0, \phi_\infty) \in \widetilde{\mathcal{D}}'(\overline{\mathbb{R}})$ that are a positive measure on \mathbb{R} .

If $\phi \in \mathcal{F}_{\{\infty\}}$, we denote by μ_ϕ the unique positive Borel measure on \mathbb{R} that satisfies

$$\phi_0(f) = \int_{\mathbb{R}} f(x) \frac{d\mu_\phi(x)}{1+x^2}, \quad f \in \mathcal{D}(\mathbb{R}). \quad (2.3)$$

◇

2.5 Remark. On first sight, introducing the factor $(1+x^2)^{-1}$ in the definition of μ_ϕ may seem artificial, but in fact it is not. First, this density is necessary to fit the usual framework of Herglotz integral representations of positive definite Nevanlinna function where commonly measures μ with $\int_{\mathbb{R}} (1+x^2)^{-1} d\mu(x)$ are used to integrate; we give more details in Example 3.4. Second, from the viewpoint of manifold theory adding this density means to pass from distributional densities to distributions, cf. [23, p. 145]. ◇

Note that, for each $\phi = (\phi_0, \phi_\infty) \in \mathcal{F}_{\{\infty\}}$, we have $\text{ord } \phi_0 = 0$ and therefore $\text{ord } \phi = \text{ord } \phi_\infty$.

We also use another characteristic of $\phi \in \mathcal{F}_{\{\infty\}}$ related to the order, namely

$$\text{ord}' \phi := \min \left\{ \text{ord } \psi : \psi = \phi + \sum_{k=0}^N a_k \delta_\infty^{(k)}, N \in \mathbb{N}_0, a_k \in \mathbb{R} \right\}; \quad (2.4)$$

here we denote by $\delta_\infty^{(k)}$ the k th derivative of the Dirac distribution density concentrated at the point ∞ , i.e.

$$\delta_\infty^{(k)} := (0, \delta_0^{(k)}) \in \tilde{\mathcal{D}}'(\overline{\mathbb{R}}),$$

where δ_0 is the unit point mass at 0 and $\delta_0^{(k)}$ its k th derivative.

2.6 Lemma. *Let $\phi = (\phi_0, \phi_\infty) \in \mathcal{F}_{\{\infty\}}$. Then there exists a constant $C > 0$ such that*

$$|\phi_\infty(f)| \leq C \|f\|_{\text{supp } f, \text{ord}' \phi}, \quad f \in \mathcal{D}(\mathbb{R}), 0 \notin \text{supp } f. \quad (2.5)$$

Proof. Choose ψ of the form $\phi + \sum_{k=0}^N a_k \delta_\infty^{(k)}$ with some $N \in \mathbb{N}_0$ and $a_k \in \mathbb{R}$ such that $\text{ord } \psi = \text{ord}' \phi$. Moreover, choose a partition of unity $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ subordinate to the open cover $\{(-2, 2), \overline{\mathbb{R}} \setminus [-1, 1]\}$ of $\overline{\mathbb{R}}$. Then we find a constant $C_\infty > 0$ such that, for each $f \in \mathcal{D}(\mathbb{R})$ with $0 \notin \text{supp } f$,

$$\begin{aligned} |\phi_\infty(f)| &\leq |\phi_0((\chi^\infty f) \circ \Lambda_\infty)| + \underbrace{|\phi_\infty(\chi^0 f)|}_{= \psi_\infty(\chi^0 f)} \\ &\leq \|f\|_{[-1, 1], 0} \int_{[-1, 1]} \frac{d\mu_\phi(x)}{1+x^2} + C_\infty \|f\|_{[-2, 2], \text{ord } \psi_\infty}. \end{aligned}$$

□

Of course, using the transformation law (2.2) we also find an estimate

$$|\phi_\infty(f)| \leq C_\varepsilon \|f\|_{\text{supp } f, 0}, \quad f \in \mathcal{D}(\mathbb{R}), [-\varepsilon, \varepsilon] \cap \text{supp } f = \emptyset.$$

In contrast to (2.5), here the constant C_ε depends on ε .

The class of measures that may appear as μ_ϕ with some $\phi \in \mathcal{F}_{\{\infty\}}$ turns out to be the one that is introduced in the following definition.

2.7 Definition. Let μ be a scalar-valued positive Borel measure on the real line. Then we say that μ belongs to the class \mathbb{M} if there exists a number $n \in \mathbb{N}_0$ such that

$$\int_{\mathbb{R}} \frac{d\mu(x)}{(1+x^2)^{n+1}} < \infty. \quad (2.6)$$

If $\mu \in \mathbb{M}$, we denote by $\Delta(\mu)$ the minimal non-negative integer n such that (2.6) holds. ◇

In the next theorem we make the relation between $\mathcal{F}_{\{\infty\}}$ and \mathbb{M} explicit.

2.8 Theorem. *The following statements hold.*

- (i) *Let $\mu \in \mathbb{M}$. Then there exists a distributional density $\phi \in \mathcal{F}_{\{\infty\}}$ with $\mu_\phi = \mu$.*
- (ii) *Let $\phi \in \mathcal{F}_{\{\infty\}}$. Then $\mu_\phi \in \mathbb{M}$ and*

$$\text{ord}' \phi = \min \left\{ n \in \mathbb{N}_0 : \int_{\mathbb{R}} \frac{d\mu_\phi(x)}{(1+|x|)^{n+2}} < \infty \right\}. \quad (2.7)$$

In particular,

$$\Delta(\mu_\phi) = \left\lfloor \frac{\text{ord}' \phi + 1}{2} \right\rfloor \leq \left\lfloor \frac{\text{ord} \phi + 1}{2} \right\rfloor. \quad (2.8)$$

Here $\lfloor x \rfloor$ denotes the largest integer less than or equal to x .

- (iii) *Let $\phi \in \mathcal{F}_{\{\infty\}}$ and $\psi \in \tilde{\mathcal{D}}'(\overline{\mathbb{R}})$. Then $\psi \in \mathcal{F}_{\{\infty\}}$ and $\mu_\psi = \mu_\phi$ if and only if there exist $N \in \mathbb{N}$ and $a_0, \dots, a_N \in \mathbb{R}$ with*

$$\psi = \phi + \sum_{k=0}^N a_k \delta_\infty^{(k)}. \quad (2.9)$$

\Rightarrow *Notice:* Analogous of some parts of this theorem are stated (mostly without proofs) in [24] and, somewhat more elaborate, in [29]. However, there one works in the vicinity of a finite point instead of ∞ and with compactly supported distributions. Instead of carrying out the techniques necessary to reduce to the (anyway not explicitly given) arguments in [24], we prefer to give self-contained proofs for all assertions. \diamond

Before we come to the proof of the theorem, we show a lemma, which is also used in later sections.

2.9 Lemma. *Let $\mu \in \mathbb{M}$ and let $n \in \mathbb{N}_0$ such that*

$$\int_{\mathbb{R}} \frac{d\mu(x)}{(1+|x|)^{n+2}} < \infty. \quad (2.10)$$

Moreover, let $\chi_-^0, \chi_\infty^\infty \in C^\infty(\overline{\mathbb{R}})$ be a partition of unity subordinate to the open cover $\{(-2, 2), \overline{\mathbb{R}} \setminus [-1, 1]\}$. Define

$$\begin{aligned} \phi_0(f) &:= \int_{\mathbb{R}} f(x) \frac{d\mu(x)}{1+x^2}, \\ \phi_\infty(f) &:= \int_{\mathbb{R} \setminus \{0\}} \left[f\left(\frac{1}{x}\right) - \chi_\infty^\infty(x) \sum_{k=0}^{n-1} \frac{f^{(k)}(0)}{k!} \left(\frac{1}{x}\right)^k \right] \frac{d\mu(x)}{1+x^2} \end{aligned} \quad (2.11)$$

for $f \in \mathcal{D}(\mathbb{R})$. Then $\phi = (\phi_0, \phi_\infty) \in \mathcal{F}_{\{\infty\}}$, $\mu_\phi = \mu$ and $\text{ord} \phi \leq n$.

Proof. First we show that the integral in the definition of ϕ_∞ is well defined and represents a distribution. Let $f \in \mathcal{D}(\mathbb{R})$. For small values of x , the second

summand in the integral is not present and we obtain the immediate estimate

$$\begin{aligned} & \int_{[-1,1] \setminus \{0\}} \left| f\left(\frac{1}{x}\right) - \chi^\infty(x) \sum_{k=0}^{n-1} \frac{f^{(k)}(0)}{k!} \left(\frac{1}{x}\right)^k \right| \frac{d\mu(x)}{1+x^2} \\ & \leq \|f\|_\infty \int_{[-1,1] \setminus \{0\}} \frac{d\mu(x)}{1+x^2}. \end{aligned} \quad (2.12)$$

For large values of x , we use Taylor's theorem to estimate

$$\begin{aligned} & \int_{\mathbb{R} \setminus (-2,2)} \left| f\left(\frac{1}{x}\right) - \chi^\infty(x) \sum_{k=0}^{n-1} \frac{f^{(k)}(0)}{k!} \left(\frac{1}{x}\right)^k \right| \frac{d\mu(x)}{1+x^2} \\ & \leq \|f^{(n)}\|_\infty \cdot \frac{1}{n!} \int_{\mathbb{R} \setminus (-2,2)} \frac{1}{|x|^n} \cdot \frac{d\mu(x)}{1+x^2}. \end{aligned} \quad (2.13)$$

The integral on the right-hand side converges because of (2.10). On the remaining intervals $(-2, -1)$ and $(1, 2)$ we have the straightforward estimate

$$\begin{aligned} & \int_{(-2,2) \setminus [-1,1]} \left| f\left(\frac{1}{x}\right) - \chi^\infty(x) \sum_{k=0}^{n-1} \frac{f^{(k)}(0)}{k!} \left(\frac{1}{x}\right)^k \right| \frac{d\mu(x)}{1+x^2} \\ & \leq \left(\|f\|_\infty + \sum_{k=0}^{n-1} \frac{\|f^{(k)}\|_\infty}{k!} \right) \int_{(-2,2) \setminus [-1,1]} \frac{d\mu(x)}{1+x^2}. \end{aligned} \quad (2.14)$$

Putting together (2.12), (2.13) and (2.14) we obtain that ϕ_∞ is a distribution, and that $\text{ord } \phi_\infty \leq n$. Since, clearly, $\text{ord } \phi_0 = 0$, we have $\text{ord } \phi \leq n$.

Next we show the transformation rule (2.1). Let $f \in \mathcal{D}(\mathbb{R})$ with $0 \notin \text{supp } f$ be given. Then $f^{(k)}(0) = 0$, $k \geq 0$, and hence (remember, we suppress the notation of Λ_0)

$$\phi_\infty(f) = \int_{\mathbb{R} \setminus \{0\}} f\left(\frac{1}{x}\right) \frac{d\mu(x)}{1+x^2} = \int_{\mathbb{R} \setminus \{0\}} [f \circ \Lambda_\infty](x) \frac{d\mu(x)}{1+x^2} = \phi_0(f \circ \Lambda_\infty).$$

Thus we have $\phi \in \mathcal{F}_{\{\infty\}}$. It follows from the definition of ϕ_0 that $\mu_\phi = \mu$. \square

Proof of Theorem 2.8. Item (i) follows immediately from Lemma 2.9.

Next we prove (iii). If ψ is of the form (2.9), then

$$\psi = \left(\phi_0, \phi_\infty + \sum_{k=0}^N a_k \delta_0^{(k)} \right),$$

and hence $\psi \in \mathcal{F}_{\{\infty\}}$ and $\mu_\psi = \mu_\phi$.

For the converse, assume that $\psi = (\psi_0, \psi_\infty) \in \mathcal{F}_{\{\infty\}}$ and $\mu_\psi = \mu_\phi$. This clearly implies that $\psi_0 = \phi_0$. Moreover, for each function $f \in \mathcal{D}(\mathbb{R})$ with $0 \notin \text{supp } f$, we have

$$\phi_\infty(f) = \phi_0(f \circ \Lambda_\infty) = \psi_0(f \circ \Lambda_\infty) = \psi_\infty(f).$$

Thus $\text{supp}(\phi_\infty - \psi_\infty) \subseteq \{0\}$, and it follows that $\phi_\infty - \psi_\infty = \sum_{k=0}^N a_k \delta_0^{(k)}$ with some $N \in \mathbb{N}$ and $a_0, \dots, a_N \in \mathbb{R}$. This shows that ϕ and ψ are related by (2.9).

Finally, we come to the proof of (ii). Let again $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ be a partition of unity subordinate to the open cover $\{(-2, 2), \overline{\mathbb{R}} \setminus [-1, 1]\}$. Moreover, choose a function $\psi \in C^\infty(\mathbb{R})$ such that

$$\psi|_{(-\infty, 1)} = 0, \quad \psi|_{(2, \infty)} = 1, \quad \psi(x) \in [0, 1], \quad x \in \mathbb{R}.$$

Set $n := \text{ord}' \phi$ and, for each $T \geq 4$, define

$$f_T(x) := \begin{cases} \chi^\infty(x) \cdot \frac{1}{x^n} \cdot \psi\left(\frac{T}{x}\right), & x \in \mathbb{R} \setminus \{0\}, \\ 0, & x = 0. \end{cases}$$

Then $f_T \in C^\infty(\mathbb{R})$ and

$$\text{supp } f_T \subseteq [1, T], \quad f_T|_{[2, \frac{T}{2}]} = \frac{1}{x^n}, \quad f_T(x) \geq 0, \quad x \in \mathbb{R}.$$

By Lemma 2.6 there exists a constant $C > 0$ such that

$$|\phi_\infty(g)| \leq C \|g\|_{[0, 1], n}, \quad g \in C^\infty(\mathbb{R}) \text{ with } \text{supp } g \subseteq (0, 1].$$

Since $\text{supp}[f_T \circ \Lambda_\infty] \subseteq [\frac{1}{T}, 1]$, it follows that

$$\begin{aligned} \int_{[2, \frac{T}{2}]} \frac{1}{x^n} \cdot \frac{d\mu_\phi(x)}{1+x^2} &\leq \int_{\mathbb{R}} f_T(x) \frac{d\mu_\phi(x)}{1+x^2} = \Phi_0(f_T) \\ &= \Phi_\infty(f_T \circ \Lambda_\infty) \leq C \|f_T \circ \Lambda_\infty\|_{[0, 1], n}. \end{aligned} \quad (2.15)$$

In order to estimate the last expression, we write explicitly:

$$[f_T \circ \Lambda_\infty](x) = \chi^\infty\left(\frac{1}{x}\right) \cdot x^n \cdot \psi(Tx), \quad x \in \text{supp}[f_T \circ \Lambda_\infty],$$

which clearly implies that $\|f_T \circ \Lambda_\infty\|_\infty \leq 1$. Next we compute, for $k = 1, \dots, n$ and $x \in [\frac{1}{T}, 1]$,

$$[f_T \circ \Lambda_\infty]^{(k)}(x) = \sum_{\substack{i, j, l \geq 0 \\ i+j+l=k}} \binom{k}{i, j, l} \left[\frac{d^i}{dx^i} \chi^\infty\left(\frac{1}{x}\right) \right] \frac{n!}{(n-j)!} x^{n-j} \cdot T^l \psi^{(l)}(Tx).$$

Since $\chi^\infty|_{[2, \infty)} = 1$, we have

$$\frac{d^i}{dx^i} \chi^\infty\left(\frac{1}{x}\right) = 0, \quad x < \frac{1}{2}, \quad i \geq 1.$$

Thus

$$c_1 := \sup \left\{ \left| \frac{d^i}{dx^i} \chi^\infty\left(\frac{1}{x}\right) \right| : x \in (0, 1], i = 0, \dots, n \right\} < \infty.$$

Since $\psi|_{[2, \infty)} = 1$ and $\psi|_{(-\infty, 1]} = 0$, we have

$$\psi^{(l)}(x) = 0, \quad x \in \mathbb{R} \setminus (1, 2), \quad l \geq 1.$$

Using the fact that $\|\psi\|_\infty = 1$ we obtain

$$c_2 := \sup \{ |\psi^{(l)}(x)| : x \in \mathbb{R}, l = 0, \dots, n \} < \infty.$$

Moreover, $\psi^{(l)}(Tx) = 0$ for $x \geq \frac{2}{T}$, $l \geq 1$, and hence

$$|x^{n-j} T^l \psi^{(l)}(Tx)| \leq \left(\frac{2}{T}\right)^{n-j} T^l c_2 = 2^{n-j} c_2 T^{l+j-n}, \quad x \in \left[\frac{1}{T}, 1\right], l \geq 1.$$

Since $l + j = k - i \leq k \leq n$, we have $T^{l+j-n} \leq 1$.

Putting together these estimates we can deduce that, for $k = 1, \dots, n$ and $x \in \left[\frac{1}{T}, 1\right]$,

$$|[f_T \circ \Lambda_\infty]^{(k)}(x)| \leq c_1 n! \cdot \left[\sum_{\substack{i,j,l \geq 0 \\ i+j+l=k}} \binom{k}{i,j,l} \right] \cdot \max\{1, 2^n c_2\}.$$

The right-hand side of (2.15) is therefore bounded independently of T . This shows that

$$\int_{[2, \infty)} \frac{1}{x^n} \cdot \frac{d\mu_\phi(x)}{1+x^2} < \infty.$$

The same argument applies on the negative semi-axis, and we see that

$$\int_{\mathbb{R}} \frac{d\mu_\phi(x)}{(1+|x|)^{2+n}} < \infty.$$

It follows that $\mu_\phi \in \mathbb{M}$ and that the inequality “ \geq ” in (2.7) holds.

For the reverse inequality, define a distributional density ψ as in Lemma 2.9 with μ replaced by μ_ϕ and n minimal so that (2.10) holds. Then $\mu_\psi = \mu_\phi$ and hence, by the already proved item (iii), ϕ and ψ differ only by a term $\sum_{k=0}^N a_k \delta_\infty^{(k)}$. This, together with Lemma 2.9 and the definition of $\text{ord}' \phi$ in (2.4), shows that

$$\text{ord}' \phi \leq \text{ord} \psi \leq n.$$

The relation (2.8) is immediate from (2.7). \square

2.10 Remark. If $\mu \in \mathbb{M}$ and $n \in \mathbb{N}_0$ is minimal such that (2.10) is valid, then the distributional density ϕ from Lemma 2.9 satisfies

$$\text{ord} \phi = \text{ord}' \phi = n;$$

this follows from the last part of the proof of Theorem 2.8. \diamond

3 Representations of $\mathcal{N}_\kappa^{(\infty)}$ -functions

The class $\mathcal{F}(\overline{\mathbb{R}})$ can be used to represent functions in $\mathcal{N}_{<\infty}$. Let us recall this fact in the formulation of [25, Proposition 5.4]. For this we need some more notation. First, we denote by $\mathbb{R}(z)$ the set of all rational functions with real coefficients. Second, for each $z \in \mathbb{C} \setminus \mathbb{R}$, let $\beta_z : \overline{\mathbb{R}} \rightarrow \mathbb{C}$ be defined by

$$\beta_z(x) := \begin{cases} \frac{1+xz}{x-z}, & x \in \mathbb{R}, \\ z, & x = \infty. \end{cases} \quad (3.1)$$

Then

$$(\beta_z \circ \Lambda_\infty^{-1})(x) = \frac{x+z}{1-xz}, \quad x \in \mathbb{R},$$

and we see that $\beta_z \in C^\infty(\overline{\mathbb{R}})$ for each $z \in \mathbb{C} \setminus \mathbb{R}$.

3.1 Theorem ([25]). *Let $\phi \in \mathcal{F}(\overline{\mathbb{R}})$ and $r \in \mathbb{R}(z)$. Then the function*

$$q(z) := r(z) + \phi(\beta_z) \tag{3.2}$$

belongs to $\mathcal{N}_{<\infty}$.

Conversely, let $q \in \mathcal{N}_{<\infty}$ be given. Then there exist unique $\phi \in \mathcal{F}(\overline{\mathbb{R}})$ and $r \in \mathbb{R}(z)$ such that

- (i) *the representation (3.2) holds;*
- (ii) *r is analytic on \mathbb{R} and $r(z) = O(1)$ as $|z| \rightarrow \infty$.*

3.2 Definition. Let $\phi \in \mathcal{F}(\overline{\mathbb{R}})$ and $r \in \mathbb{R}(z)$ be given. Then we write $q_{r,\phi}$ for the expression on the right-hand side of (3.2); if $r = 0$, we just write q_ϕ .

Let $q \in \mathcal{N}_{<\infty}$ be given. Then we write r_q and ϕ_q for the unique $r \in \mathbb{R}(z)$ and $\phi \in \mathcal{F}(\overline{\mathbb{R}})$, respectively, such that (i) and (ii) in Theorem 3.1 hold. \diamond

3.3 Remark. Since $\beta_i(x) = i$ for all $x \in \overline{\mathbb{R}}$, we have $q_\phi(i) = \phi(\beta_i) \in i\mathbb{R}$ when $\phi \in \mathcal{F}(\overline{\mathbb{R}})$. \diamond

For the purpose of illustration let us elaborate on the case when $q \in \mathcal{N}_0$ and make explicit the relation between the Herglotz integral representation (1.1) and the distributional representation (3.2).

3.4 Example. Let μ be a positive Borel measure on \mathbb{R} with

$$\int_{\mathbb{R}} \frac{d\mu(x)}{1+x^2} < \infty \tag{3.3}$$

and let $a \in \mathbb{R}$ and $b \geq 0$. Define a distributional density $\phi = (\phi_0, \phi_\infty) \in \mathcal{F}_{\{\infty\}}$ as in Lemma 2.9 with the given measure μ and the number $n = 0$. Note that, since $n = 0$, the partition of unity does not enter the formulae in (2.11). Now, set

$$\psi := \phi + b\delta_\infty.$$

Let $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ be some partition of unity subordinate to the open cover $\{\mathbb{R} \setminus \{\infty\}, \mathbb{R} \setminus \{0\}\}$. Then we obtain from (2.2) and (2.11) that

$$\begin{aligned} \psi(\beta_z) &= \phi_0(\chi^0 \beta_z) + \phi_\infty((\chi^\infty \beta_z) \circ \Lambda_\infty^{-1}) + b(\chi^\infty \beta_z)(\infty) \\ &= \int_{\mathbb{R}} \chi^0(x) \beta_z(x) \frac{d\mu(x)}{1+x^2} + \int_{\mathbb{R} \setminus \{0\}} \chi^\infty(x) \beta_z(x) \frac{d\mu(x)}{1+x^2} + bz \\ &= \int_{\mathbb{R}} \frac{1+xz}{x-z} \cdot \frac{d\mu(x)}{1+x^2} + bz = bz + \int_{\mathbb{R}} \left(\frac{1}{x-z} - \frac{x}{1+x^2} \right) d\mu(x). \end{aligned}$$

To fully match (1.1) with (3.2), it remains to notice that a rational function that has the properties in Theorem 3.1 (ii) and has no non-real poles (which holds for \mathcal{N}_0 -functions) must be equal to a real constant. \diamond

The subclass $\mathcal{N}_{<\infty}^{(\infty)}$ of $\mathcal{N}_{<\infty}$, which is defined below, is the central object in the rest of the paper.

3.5 Definition. Let $q \in \mathcal{N}_{<\infty}$. Then we say that $q \in \mathcal{N}_{<\infty}^{(\infty)}$ if

$$\lim_{z \rightarrow i\infty} \frac{q(z)}{z^{2\kappa-1}} \in (-\infty, 0) \quad \text{or} \quad \lim_{z \rightarrow i\infty} \left| \frac{q(z)}{z^{2\kappa-1}} \right| = \infty, \quad (3.4)$$

where $\kappa := \text{ind}_- q$. Here we denote by \rightarrow the non-tangential limit towards $i\infty$.

Moreover, we set $\mathcal{N}_\kappa^{(\infty)} := \{q \in \mathcal{N}_{<\infty}^{(\infty)} : \text{ind}_- q = \kappa\}$, $\kappa \in \mathbb{N}_0$. \diamond

The significance in this definition is not that the asymptotic relation (3.4) holds with *some* κ , but that it holds *exactly with* $\kappa = \text{ind}_- q$. In fact, (3.4) always holds with some $\kappa \in \mathbb{Z}$, $\kappa \leq \text{ind}_- q$.

3.6 Remark. The origin of the class $\mathcal{N}_{<\infty}^{(\infty)}$ lies in a spectral property of corresponding operator models, and also the choice of notation is explained by this fact. Namely, using the language of [32] and [34]³, a generalized Nevanlinna function q belongs to the class $\mathcal{N}_{<\infty}^{(\infty)}$ if and only if the point ∞ is a generalized pole of non-positive type with the maximal possible multiplicity, namely $\text{ind}_- q$.

The multiplicities of generalized poles of non-positive type in $\overline{\mathbb{R}}$ and the multiplicities of poles located in \mathbb{C}^+ together sum up to $\text{ind}_- q$, cf. [32, Theorem 3.5]. Hence a function q belongs to $\mathcal{N}_{<\infty}^{(\infty)}$ if and only if q neither has finite generalized poles of non-positive type nor non-real poles. Using the analytic characterization [34, Theorem 3.1] of generalized poles of non-positive type, we thus obtain the following equivalence:

$$q \in \mathcal{N}_{<\infty}^{(\infty)} \quad \Longleftrightarrow \quad \begin{array}{l} q \text{ has no non-real poles and} \\ \lim_{z \rightarrow x} (z-x)q(z) \in (-\infty, 0] \quad \text{for every } x \in \mathbb{R}. \end{array}$$

Using the analytic characterization [34, Theorem 3.2] of the multiplicity of a generalized pole of non-positive type, we see that, for a function $q \in \mathcal{N}_{<\infty}^{(\infty)}$, the negative index $\text{ind}_- q$ can be recovered from the asymptotics of q at $i\infty$; namely, $\text{ind}_- q$ is the unique number $\kappa \in \mathbb{N}_0$ such that (3.4) holds and

$$\lim_{z \rightarrow i\infty} \frac{q(z)}{z^{2\kappa+1}} = 0.$$

\diamond

Let us recall some properties of $\mathcal{N}_{<\infty}^{(\infty)}$ -functions. Their proof is immediate from what we said above; we skip the details.

3.7 Lemma. *We have $\mathcal{N}_0 = \mathcal{N}_0^{(\infty)} \subseteq \mathcal{N}_{<\infty}^{(\infty)}$ and $\mathbb{R}[z] \subseteq \mathcal{N}_{<\infty}^{(\infty)}$. If $q_1, q_2 \in \mathcal{N}_{<\infty}^{(\infty)}$, then also $q_1 + q_2 \in \mathcal{N}_{<\infty}^{(\infty)}$ and*

$$\text{ind}_-(q_1 + q_2) \leq \max \{ \text{ind}_- q_1, \text{ind}_- q_2 \}.$$

In this relation strict inequality may occur only if $\text{ind}_- q_1 = \text{ind}_- q_2$ and for both functions the second relation in (3.4) holds.

³As common in the recent literature, we substitute the terminology “negative type” in these references by “non-positive type”.

An example where the strict inequality in the previous lemma occurs is $q_1(z) = z^2 + z$, $q_2(z) = -z^2$.

3.8 Remark. A function q belongs to $\mathcal{N}_{<\infty}^{(\infty)}$ if and only if it can be written as

$$q(z) = (z^2 + 1)^m q_0(z) + p(z) \quad (3.5)$$

where $m \in \mathbb{N}_0$, $q_0 \in \mathcal{N}_0$ and $p \in \mathbb{R}[z]$; see, e.g. [10]. \diamond

In the next theorem we show in detail that functions of the class $\mathcal{N}_{<\infty}^{(\infty)}$ correspond precisely to distributional densities of the class $\mathcal{F}_{\{\infty\}}$. In its formulation remember the notation in Definition 3.2.

3.9 Theorem. *The classes $\mathcal{N}_{<\infty}^{(\infty)}$, $\mathcal{F}_{\{\infty\}}$ and \mathbb{M} are related as follows.*

- (i) *Let $\phi = (\phi_0, \phi_\infty) \in \mathcal{F}_{\{\infty\}}$ and $r \in \mathbb{R}$; then $q_{r,\phi} \in \mathcal{N}_{<\infty}^{(\infty)}$. Moreover, define the functions $g_T(x) := x^{\text{ord } \phi} \chi^0(Tx)$, $x \in \mathbb{R}$, where χ^0 denotes a $C^\infty(\mathbb{R})$ -function with $\text{supp } \chi^0 \subseteq (-2, 2)$, $\chi^0|_{[-1,1]} = 1$ and $\chi^0(x) \in [0, 1]$, $x \in \mathbb{R}$. Then*

$$\text{ind}_- q_{r,\phi} = \left\lfloor \frac{\text{ord } \phi}{2} \right\rfloor + \begin{cases} 0 & \text{if } \text{ord } \phi \text{ is even and } \lim_{T \rightarrow \infty} \phi_\infty(g_T) \geq 0, \\ 1 & \text{otherwise.} \end{cases} \quad (3.6)$$

The limit on the right-hand side of (3.6) always exists.

- (ii) *Let $q \in \mathcal{N}_{<\infty}^{(\infty)}$. Then $\phi_q \in \mathcal{F}_{\{\infty\}}$ and r_q is a real constant: $r_q = \text{Re } q(i)$. The measure μ_{ϕ_q} can be recovered by means of Stieltjes' inversion formula: for each compact interval $[a, b] \subseteq \mathbb{R}$,*

$$\mu_{\phi_q}([a, b]) = \frac{1}{\pi} \lim_{\delta \searrow 0} \lim_{\varepsilon \searrow 0} \int_{a-\delta}^{b+\delta} \text{Im } q(x + i\varepsilon) dx. \quad (3.7)$$

For the mass at a point $c \in \mathbb{R}$ one has

$$\mu_{\phi_q}(\{c\}) = - \lim_{\varepsilon \searrow 0} i\varepsilon q(c + i\varepsilon). \quad (3.8)$$

- (iii) *Let $\phi \in \mathcal{F}_{\{\infty\}}$ and $\psi \in \widetilde{\mathcal{D}}'(\overline{\mathbb{R}})$. Then $\psi \in \mathcal{F}_{\{\infty\}}$ and $\mu_\phi = \mu_\psi$ if and only if $p := q_\phi - q_\psi$ is a real polynomial with $\text{Re } p(i) = 0$.*
- (iv) *Let $q_1, q_2 \in \mathcal{N}_{<\infty}^{(\infty)}$. Then $\mu_{\phi_{q_1}} = \mu_{\phi_{q_2}}$ if and only if $q_1 - q_2$ is a real polynomial.*
- (v) *Let $\mu \in \mathbb{M}$. Then*

$$\{\text{ind}_- q_\phi : \phi \in \mathcal{F}_{\{\infty\}}, \mu_\phi = \mu\} = \{n \in \mathbb{N}_0 : n \geq \Delta(\mu)\}.$$

To shorten notation, we sometimes write

$$\mu_q := \mu_{\phi_q} \quad \text{for } q \in \mathcal{N}_{<\infty}^{(\infty)}.$$

\Rightarrow *Notice:* For the reader with experience in the theory of Pontryagin space operator models, some of these assertions are of course not surprising. Indeed,

for some parts, a proof alternative to the one given below could proceed via analysing the operator model. It would require to put together knowledge (explicitly and implicitly) contained in [34], [24] and [27]. We prefer to give an approach as elementary as possible for all parts of the theorem; all we need to know about the operator model is what we summarized in Remark 3.6. \diamond

Proof of Theorem 3.9. To start with, let $\phi = (\phi_0, \phi_\infty) \in \mathcal{F}_{\{\infty\}}$ and $r \in \mathbb{R}$ be given, and let us show that $q_{r,\phi} \in \mathcal{N}_{<\infty}^{(\infty)}$. Clearly, this function has no non-real poles. Let $x_0 \in \mathbb{R}$, choose $T > 0$ such that $|x_0| < T$, and choose a partition of unity $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ subordinate to the open cover

$$\{(-2T, 2T), \overline{\mathbb{R}} \setminus [-T, T]\}.$$

Then we have

$$q_{r,\phi}(z) = r + \phi_0(\chi^0 \beta_z) + \phi_\infty((\chi^\infty \beta_z) \circ \Lambda_\infty^{-1}).$$

The second summand can be written as

$$\phi_0(\chi^0 \beta_z) = \int_{(-2T, 2T)} \beta_z(t) \cdot \chi^0(t) \frac{d\mu_\phi(t)}{1+t^2}$$

and hence belongs to the class \mathcal{N}_0 . The first and third summands are analytic on $\mathbb{C} \setminus [-T, T]$. Thus the point x_0 is not a generalized pole of non-positive type for any of the summands, and hence also not for their sum. We conclude that $q_{r,\phi}$ has no finite generalized poles of non-positive type, and hence belongs to the class $\mathcal{N}_{<\infty}^{(\infty)}$.

We come to the proof of (ii). Let $q \in \mathcal{N}_{<\infty}^{(\infty)}$ be given and consider the representation $q(z) = r_q(z) + \phi_q(\beta_z)$ guaranteed by Theorem 3.1. Since q has no non-real poles, the function r_q is a real constant. Moreover, $r_q = \operatorname{Re} q(i)$ because $\phi_q(\beta_i) \in i\mathbb{R}$ by Remark 3.3.

We have to show that $\phi_q \in \mathcal{F}_{\{\infty\}}$. To this end, write $\phi_q = (\phi_0, \phi_\infty)$ and let $T > 0$ be such that $s(\phi_q) \setminus \{\infty\} \subseteq (-T, T)$. Choose a partition of unity $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ subordinate to the open cover $\{(-T-1, T+1), \overline{\mathbb{R}} \setminus [-T, T]\}$ and set

$$q_0(z) := \phi_0(\chi^0 \beta_z), \quad q_\infty(z) := \phi_\infty((\chi^\infty \beta_z) \circ \Lambda_\infty^{-1}),$$

so that $q = q_0 + q_\infty$. The function q_∞ is analytic on some neighbourhood of $[-T, T]$, and hence, for every $x_0 \in [-T, T]$,

$$\lim_{z \rightarrow x_0} (z - x_0) q_0(z) = \lim_{z \rightarrow x_0} (z - x_0) q(z) \in (-\infty, 0]$$

since q has no finite generalized poles of non-positive type. The function q_0 itself is analytic in $\mathbb{C} \setminus \operatorname{supp} \chi^0$, and it follows that

$$\lim_{z \rightarrow x_0} (z - x_0) q_0(z) = 0 \quad \text{for } x_0 \in (-\infty, -T-1] \cup [T+1, \infty).$$

The relations $\beta_z^{(n)}(x) = (-1)^n n! (1+z^2)(x-z)^{-(n+1)}$, $n \geq 1$, (here differentiation is with respect to x) imply that

$$\sup_{y \geq 1} \|\beta_{iy}\|_{\operatorname{supp} \chi_0, \operatorname{ord} \phi_0} < \infty.$$

Moreover,

$$\lim_{y \rightarrow +\infty} \frac{1}{y} q_0(iy) = 0.$$

Let $x_0 \in (-T-1, -T) \cup (T, T+1)$. Choose $\varepsilon > 0$ with $[x_0 - 2\varepsilon, x_0 + 2\varepsilon] \subseteq (-T-1, -T) \cup (T, T+1)$, and a partition of unity $\tilde{\chi}^0, \tilde{\chi}^\infty \in C^\infty(\overline{\mathbb{R}})$ subordinate to the open cover $\{(x_0 - 2\varepsilon, x_0 + 2\varepsilon), \overline{\mathbb{R}} \setminus [x_0 - \varepsilon, x_0 + \varepsilon]\}$. Then the function $(\tilde{\chi}^\infty \chi^0 \phi_0)(\beta_z)$ is analytic in a neighbourhood of $[x_0 - \varepsilon, x_0 + \varepsilon]$. Since ϕ is a positive measure on $(-T-1, -T) \cup (T, T+1)$, say μ , we have

$$(\tilde{\chi}^0 \chi^0 \phi_0)(\beta_z) = \int_{\mathbb{R}} \beta_z(x) \cdot \tilde{\chi}^0(x) \chi^0(x) d\mu(x),$$

and hence

$$\lim_{z \rightarrow x_0} (z - x_0) q_0(z) = \lim_{z \rightarrow x_0} (z - x_0) (\tilde{\chi}^0 \chi^0 \phi_0)(\beta_z) = -\mu(\{x_0\}) \in (-\infty, 0].$$

Altogether, we see that the function q_0 has no generalized poles of non-positive type. Clearly, it also has no non-real poles, and it follows that $q_0 \in \mathcal{N}_0$. Thus we find a positive measure σ supported in $[-T-1, T+1]$ such that

$$\phi_0(\chi^0 \beta_z) = q_0(z) = \int_{\mathbb{R}} \beta_z(x) d\sigma(x).$$

Since a compactly supported distribution is uniquely determined by its Cauchy transform (see, e.g. [5, Theorem 2.3.3]), it follows that ϕ_0 is equal to the measure σ on $(-T, T)$. Letting T tend to infinity we can deduce that ϕ_0 is a measure on \mathbb{R} .

The fact that μ_{ϕ_q} can be recovered by means of the Stieltjes inversion formula in (3.7) was proved in [25, Lemma 5.5]. On comparing the present formulation with this reference, remember that we included the density $\frac{1}{1+x^2}$ in the definition μ_{ϕ_q} . Formula (3.8) can be proved in a similar way as [25, Lemma 5.5] by choosing a partition of unity and reducing to the positive definite case. This completes the proof of (ii).

Next, we show item (iii). Consider the function $\check{\beta}_z := \beta_z \circ \Lambda_\infty^{-1}$, i.e.

$$\check{\beta}_z(x) = \frac{x+z}{1-xz}, \quad x \in \mathbb{R}.$$

A simple computation gives (again differentiation is with respect to x)

$$\check{\beta}_z(0) = z, \quad \check{\beta}_z^{(n)}(0) = (1+z^2)n!z^{n-1}, \quad n \in \mathbb{N}.$$

We see that $\{\check{\beta}_z^{(n)}(0) : n \in \mathbb{N}_0\}$ is a basis for the real vector space

$$\begin{aligned} & \{b_m z^m + \dots + b_1 z + b_0 : m \in \mathbb{N}_0, b_j \in \mathbb{R}, b_0 + b_2 + \dots = 0\} \\ & = \{p \in \mathbb{R}[z] : \operatorname{Re} p(i) = 0\}. \end{aligned}$$

Hence a function p is a real polynomial with $\operatorname{Re} p(i) = 0$ if and only if it can be represented as

$$p(z) = \left(\sum_{k=0}^N a_k \delta_\infty^{(k)} \right) (\beta_z)$$

with some $N \in \mathbb{N}_0$ and $a_0, \dots, a_N \in \mathbb{R}$. Now the assertion follows from Theorem 2.8 (iii) and the uniqueness statement in the converse part of Theorem 3.1.

Item (iv) follows immediately from (iii) and the representations $q_i(z) = r_{q_i} + q_{\phi_{q_i}}(z)$, $i = 1, 2$, with $r_{q_i} \in \mathbb{R}$.

For the proof of (v), let $\mu \in \mathbb{M}$ be given and set $\Delta := \Delta(\mu)$. Consider the function

$$q(z) := (1 + z^2)^\Delta \int_{\mathbb{R}} \beta_z(x) \frac{d\mu(x)}{(1 + x^2)^{\Delta+1}}. \quad (3.9)$$

The integral term belongs to the class \mathcal{N}_0 and hence has no generalized poles of non-positive type. It follows that also q has no finite generalized poles of non-positive type. Clearly, q has no non-real poles, and hence $q \in \mathcal{N}_{<\infty}^{(\infty)}$. Let $a, b \in \mathbb{R}$ with $a < b$, choose $T > 0$ such that $[a, b] \subseteq (-T, T)$, and choose a partition of unity $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ subordinate to the open cover

$$\{(-2T, 2T), \overline{\mathbb{R}} \setminus [-T, T]\}.$$

Using $\beta_z(t) = (\frac{1}{t-z} - \frac{t}{1+t^2})(1+t^2)$ we can rewrite q as follows

$$\begin{aligned} q(z) &= (1 + z^2)^\Delta \int_{\mathbb{R}} \frac{1}{t-z} \cdot \frac{\chi^0(t)d\mu(t)}{(1+t^2)^\Delta} \\ &\quad - (1 + z^2)^\Delta \int_{\mathbb{R}} \frac{t}{1+t^2} \cdot \frac{\chi^0(t)d\mu(t)}{(1+t^2)^\Delta} + (1 + z^2)^\Delta \int_{\mathbb{R}} \beta_z(t) \frac{\chi^\infty(t)d\mu(t)}{(1+t^2)^\Delta}. \end{aligned}$$

The second and third summands are analytic in a neighbourhood of $(-T, T)$. The integral in the first summand is a Cauchy integral of a finite measure. Using (3.7) and the Stieltjes–Lifshitz inversion formula (e.g. as in [19, Theorem 1.2.4]) we obtain

$$\begin{aligned} \mu_{\phi_q}([a, b]) &= \frac{1}{\pi} \lim_{\delta \searrow 0} \lim_{\varepsilon \searrow 0} \int_{a-\delta}^{b+\delta} \operatorname{Im} q(x + i\varepsilon) dx \\ &= \frac{1}{\pi} \lim_{\delta \searrow 0} \lim_{\varepsilon \searrow 0} \int_{a-\delta}^{b+\delta} \operatorname{Im} \left[(1 + (x + i\varepsilon)^2)^\Delta \int_{\mathbb{R}} \frac{1}{t - (x + i\varepsilon)} \cdot \frac{\chi^0(t)d\mu(t)}{(1+t^2)^\Delta} \right] dx \\ &= \int_{[a, b]} (1 + x^2)^\Delta \cdot \frac{\chi^0(x)d\mu(x)}{(1+x^2)^\Delta} = \mu([a, b]). \end{aligned}$$

Since a and b were arbitrary, this shows that $\mu_{\phi_q} = \mu$. Moreover, $\operatorname{Re} q(i) = 0$ and hence $q = q_{\phi_q}$. By the already proved item (iii) we have

$$\{q_\phi : \phi \in \mathcal{F}_{\{\infty\}}, \mu_\phi = \mu\} = \{q + p : p \in \mathbb{R}[z], \operatorname{Re} p(i) = 0\}.$$

The negative index of a function of the form $q + p$ with q from (3.9) and $p \in \mathbb{R}[z]$ was computed in [31, Lemma 3.3], namely, write $p(z) = b_m z^m + \dots + b_1 z + b_0$ with $b_m \neq 0$ if $p \neq 0$ and set $m = -1$ if $p = 0$; then

$$\operatorname{ind}_-(q + p) = \max \left\{ \Delta, \left\lfloor \frac{m+1}{2} \right\rfloor \right\} - \begin{cases} 1, & m > 2\Delta, m \text{ odd}, b_m > 0, \\ 0, & \text{otherwise.} \end{cases} \quad (3.10)$$

From this formula it is obvious that $\operatorname{ind}_-(q + p)$ covers the set $\{n \in \mathbb{N}_0 : n \geq \Delta\}$ when p varies through all real polynomials with $\operatorname{Re} p(i) = 0$.

Finally, we turn to the formula (3.6) for the negative index. Clearly, it is enough to consider the case when $r = 0$. Let $\phi \in \mathcal{F}_{\{\infty\}}$ be given and set $\Delta := \Delta(\mu_\phi)$. Moreover, fix a partition of unity $\chi^0, \chi^\infty \in C^\infty(\mathbb{R})$ subordinate to the open cover $\{(-2, 2), \mathbb{R} \setminus [-1, 1]\}$.

Set $n := \text{ord}' \phi$. By Theorem 2.8 (ii), n satisfies (2.10). Hence we can apply Lemma 2.9 with μ replaced by μ_ϕ . This yields a distributional density, which we call ψ . Then $\mu_\psi = \mu_\phi$ and, by Remark 2.10, we have

$$\text{ord } \psi = n = \text{ord}' \phi.$$

Set again $\check{\beta}_z(t) := \beta_z(\frac{1}{t})$. A short computation shows that

$$\check{\beta}_z\left(\frac{1}{x}\right) - \sum_{k=0}^{n-1} \frac{\check{\beta}^{(k)}(0)}{k!} \left(\frac{1}{x}\right)^k = (1+z^2)z^{n-1} \frac{1}{x^{n-1}} \cdot \frac{1}{x-z}, \quad x \in \mathbb{R} \setminus \{0\}.$$

Hence

$$\begin{aligned} q_\psi(z) &= \psi(\beta_z) = \psi_0(\chi^0 \beta_z) + \psi_\infty((\chi^\infty \beta_z) \circ \Lambda_\infty^{-1}) \\ &= \int_{\mathbb{R}} \beta_z(x) \frac{\chi^0(x) d\mu_\phi(x)}{1+x^2} + (1+z^2)z^{n-1} \int_{\mathbb{R} \setminus \{0\}} \frac{1}{x-z} \cdot \frac{\chi^\infty(x) d\mu_\phi(x)}{x^{n-1}(1+x^2)}. \end{aligned}$$

Using the dominated convergence theorem for each of the integrals we obtain

$$\lim_{y \rightarrow +\infty} \frac{1}{y^{n+1}} q_\psi(iy) = 0. \quad (3.11)$$

Consider the function q defined by (3.9) with μ replaced by μ_ϕ . The integral in (3.9) belongs to the class \mathcal{N}_0 and (obviously) has no linear term in its Herglotz integral representation, which implies that

$$\lim_{y \rightarrow +\infty} \frac{1}{y^{2\Delta+1}} q(iy) = 0. \quad (3.12)$$

Since $\text{Re } q(i) = 0$, we can write $q(z) = \theta(\beta_z)$ with some $\theta \in \mathcal{F}_{\{\infty\}}$. Since $\mu_\theta = \mu_\phi = \mu_\psi$ by the previous part of the proof, it follows from Theorem 2.8 (iii) that there exist $N, M \in \mathbb{N}_0 \cup \{-1\}$ and $a_k, b_k \in \mathbb{R}$ such that

$$\phi = \theta + \sum_{k=0}^N a_k \delta_\infty^{(k)}, \quad \psi = \theta + \sum_{k=0}^M b_k \delta_\infty^{(k)}, \quad (3.13)$$

where we set $N = -1$ and $a_0 = 0$ if the sum in the expression for ϕ is not present, and otherwise, we choose N such that $a_N \neq 0$; in a similar way M and b_M are chosen. From this we obtain the following representations

$$q_\phi(z) = q(z) + a_0 z + \sum_{k=1}^N a_k (1+z^2) k! z^{k-1}, \quad (3.14)$$

$$q_\psi(z) = q(z) + b_0 z + \sum_{k=1}^M b_k (1+z^2) k! z^{k-1}. \quad (3.15)$$

The number 2Δ equals either $\text{ord}' \phi$ or $\text{ord}' \phi + 1$ depending whether $\text{ord}' \phi$ is even or odd. The relation (3.15), together with (3.11) and (3.12), implies that $M \leq 2\Delta - 1$. Using (3.14) and again [31, Lemma 3.3], cf. (3.10), we obtain

$$\text{ind}_- q_\phi = \max \left\{ \Delta, \left\lfloor \frac{N}{2} \right\rfloor + 1 \right\} - \begin{cases} 1, & N \geq 2\Delta, N \text{ even}, a_N > 0, \\ 0, & \text{otherwise.} \end{cases} \quad (3.16)$$

We have to relate the right-hand side to the order of ϕ . From (3.13) we have

$$\phi = \psi + \sum_{k=0}^N a_k \delta_\infty^{(k)} - \sum_{k=0}^M b_k \delta_\infty^{(k)}, \quad (3.17)$$

and (2.8) implies that

$$\text{ord } \psi = \text{ord}' \phi \in \{2\Delta - 1, 2\Delta\}. \quad (3.18)$$

Moreover,

$$N \leq \text{ord } \phi \quad (3.19)$$

since otherwise, we would have $M \leq 2\Delta - 1 \leq \text{ord } \psi \leq \text{ord } \phi < N$, which contradicts (3.17). The following implications give some preliminary information about $\text{ord } \phi$:

$$N \leq 2\Delta - 1 \implies \text{ord } \phi = \text{ord } \psi, \quad (3.20)$$

$$N \geq 2\Delta \implies \text{ord } \phi = N. \quad (3.21)$$

To show (3.20), assume that $N \leq 2\Delta - 1$ and $\text{ord } \phi \neq \text{ord } \psi$; then $\text{ord } \phi > \text{ord } \psi \geq 2\Delta - 1 \geq M, N$, which contradicts (3.17). Likewise, to show (3.21), assume that $N \geq 2\Delta$ and $\text{ord } \phi \neq N$; then, by (3.19), $N > \text{ord } \phi \geq \text{ord } \psi$ and $N \geq 2\Delta > M$, which again is a contradiction to (3.17).

Next we consider the limit $\lim_{T \rightarrow \infty} \Phi_\infty(g_T)$ that appears on the right-hand side of (3.6). Note that

$$\delta_0^{(k)}(g_T) = (-1)^k \delta_0(g_T^{(k)}) = \begin{cases} (-1)^k k! & \text{if } k = \text{ord } \phi, \\ 0 & \text{otherwise.} \end{cases}$$

Since $n = \text{ord}' \phi \leq \text{ord } \phi$, the regularizing term in the formula for Φ_∞ in (2.11) is not present if we apply ψ_∞ to g_T , and hence

$$\psi_\infty(g_T) = \int_{\mathbb{R} \setminus \{0\}} \frac{1}{x^{\text{ord } \phi}} \chi^0\left(\frac{T}{x}\right) \frac{d\mu_\phi(x)}{1+x^2}.$$

The dominated convergence theorem implies that this expression tends to 0 as $T \rightarrow \infty$. From this and (3.17) it follows that

$$\begin{aligned} \lim_{T \rightarrow \infty} \Phi_\infty(g_T) &= \lim_{T \rightarrow \infty} \left(\sum_{k=0}^N a_k \delta_0^{(k)}(g_T) - \sum_{k=0}^M b_k \delta_0^{(k)}(g_T) \right) \\ &= (-1)^N N! a_N \delta_{N, \text{ord } \phi} - (-1)^M M! b_M \delta_{M, \text{ord } \phi}, \end{aligned} \quad (3.22)$$

where $\delta_{i,j}$ denotes the usual Kronecker delta.

In order to show (3.6), we distinguish two cases. First, assume that $N < \text{ord } \phi$. Then $N \leq 2\Delta - 1$ by (3.21), and hence $\lfloor \frac{N}{2} \rfloor + 1 \leq \Delta$. This, together with (3.16), implies that

$$\text{ind}_- q_\phi = \max \left\{ \Delta, \left\lfloor \frac{N}{2} \right\rfloor + 1 \right\} = \Delta$$

and hence $\text{ord } \phi = \text{ord } \psi$ by (3.20). From the relations $N \leq 2\Delta - 1$ and (3.20) we obtain that $\text{ord } \phi = \text{ord } \psi$, and hence, with (3.18),

$$\begin{aligned} \text{ind}_- q_\phi = \Delta &= \begin{cases} \frac{\text{ord } \phi}{2} & \text{if } \text{ord } \phi \text{ is even,} \\ \frac{\text{ord } \phi + 1}{2} & \text{otherwise,} \end{cases} \\ &= \left\lfloor \frac{\text{ord } \phi}{2} \right\rfloor + \begin{cases} 0 & \text{if } \text{ord } \phi \text{ is even,} \\ 1 & \text{otherwise.} \end{cases} \end{aligned}$$

If $\text{ord } \phi$ is even, then $M, N \leq 2\Delta - 1 < \text{ord } \phi$ and therefore $\lim_{T \rightarrow \infty} \phi_\infty(g_T) = 0$, which completes the proof of (3.6) in the case when $N < \text{ord } \phi$.

Second, assume that $N = \text{ord } \phi$ (note that $N > \text{ord } \phi$ is excluded by (3.19)). Then

$$\left\lfloor \frac{N}{2} \right\rfloor + 1 = \left\lfloor \frac{\text{ord } \phi}{2} \right\rfloor + 1 \geq \left\lfloor \frac{\text{ord } \psi}{2} \right\rfloor + 1 \geq \left\lfloor \frac{2\Delta - 1}{2} \right\rfloor + 1 = \Delta$$

by (3.18). Now it follows from (3.16) that

$$\text{ind}_- q_\phi - \left\lfloor \frac{\text{ord } \phi}{2} \right\rfloor + \begin{cases} 0, & N \geq 2\Delta, N \text{ even, } a_N > 0, \\ 1 & \text{otherwise.} \end{cases}$$

If N is even, then $N = \text{ord } \phi \geq \text{ord } \psi \geq 2\Delta - 1$ and hence $N \geq 2\Delta$, $M < \text{ord } \phi$ and $\lim_{T \rightarrow \infty} \phi_\infty(g_T) = N!a_N$. Therefore

$$\begin{aligned} N \geq 2\Delta, N \text{ even, } a_N > 0 &\iff N \text{ even, } a_N < 0 \\ &\iff \text{ord } \phi \text{ even, } \lim_{T \rightarrow \infty} \phi_\infty(g_T) \geq 0. \end{aligned}$$

This completes the proof of (3.6) also in the case when $N = \text{ord } \phi$. \square

\Rightarrow *Notice:* In connection with the proof of item (v) and the relation (3.6) again one observation is in order. We use the function q_ψ to compute the order and the function q to compute the negative index. Therefore we have to relate these two functions, which is done in (3.15). Alternatively, one could carry out an argument modelled after the proof of [31, Lemma 3.3] (which is elementary) to show an analogue of the formula (3.10) for q_ψ in place of q . Yet alternatively, one could proceed (with the usual technical efforts of switching the roles of 0 and ∞ and reducing to compactly supported distributions) via the operator model constructed in [24], appeal to the formula for negative index of spaces in [24, Theorem 2.5] and to the relation with negative index of functions provided in [27, Corollary 3.5]. \diamond

4 Distributional densities associated with symmetric \mathcal{N}_κ -functions

We call a generalized Nevanlinna function $q \in \mathcal{N}_{<\infty}$ *symmetric* if it is an odd function, i.e. $q(-z) = -q(z)$; see, e.g. [25, Definition 1.1]. Further, we call a distributional density $\phi = (\phi_0, \phi_\infty)$ *symmetric* if ϕ_0 and ϕ_∞ both annihilate all odd test functions; see, e.g. [25, Definition 5.8]. The following fact was shown in [25, Theorem 5.9 (ii)].

4.1 Theorem ([25]). *Let $q \in \mathcal{N}_{<\infty}$, and let $r \in \mathbb{R}(z)$ and $\phi \in \mathcal{F}(\overline{\mathbb{R}})$ be the unique data in the distributional representation (3.2). Then q is symmetric if and only if r is odd and ϕ is symmetric.*

If $q \in \mathcal{N}_{<\infty}$ is symmetric, then two functions q_+ and q_- are well defined by

$$q_+(z^2) = zq(z), \quad q_-(z^2) = \frac{q(z)}{z}. \quad (4.1)$$

It was shown in [25, Proposition 3.2] that q_+ and q_- also belong to the class $\mathcal{N}_{<\infty}$ and that

$$\text{ind}_- q = \text{ind}_- q_+ + \text{ind}_- q_-.$$

In Theorem 4.4 below we determine the distributional representations of q_+ and q_- explicitly in terms of the representation of q . Before that, we show two preparatory results on distributional densities ϕ where we introduce the decomposition of ϕ corresponding to the construction of q_\pm . For this, we introduce the functions

$$h_0(t) := \begin{cases} \frac{1+t^2}{1+t^4}, & t \in \mathbb{R}, \\ 0, & t = \infty, \end{cases} \quad h_1(t) := \begin{cases} \frac{t^2(1+t^2)}{1+t^4}, & t \in \mathbb{R}, \\ 1, & t = \infty. \end{cases} \quad (4.2)$$

Clearly, $h_0, h_1 \in C^\infty(\overline{\mathbb{R}})$ and

$$h_1\left(\frac{1}{t}\right) = h_0(t), \quad t \in \overline{\mathbb{R}}. \quad (4.3)$$

Moreover, for a real-valued function $g \in C^\infty(\mathbb{R})$ that satisfies $\lim_{|x| \rightarrow \infty} |g(x)| = \infty$, we denote by C_g the operator of composition with g , i.e. $[C_g(f)](x) = f(g(x))$, $x \in \mathbb{R}$, for $f \in \mathcal{D}(\mathbb{R})$. Then, for each distribution $\phi \in \mathcal{D}'(\mathbb{R})$, also the map $\phi \circ C_g$ belongs to $\mathcal{D}'(\mathbb{R})$. If $g \in C^\infty(\overline{\mathbb{R}})$, then one can define $C_g(f)$ in a similar way for $f \in C^\infty(\overline{\mathbb{R}})$, so that $C_g(f) \in C^\infty(\overline{\mathbb{R}})$. Moreover, set $\tau(t) := t^2$, $t \in \mathbb{R}$, and extend it to $\overline{\mathbb{R}}$ by $\tau(\infty) = \infty$.

4.2 Lemma. *Let $\phi = (\phi_0, \phi_\infty) \in \tilde{\mathcal{D}}'(\overline{\mathbb{R}})$. Then $\phi^+ := (\phi_0^+, \phi_\infty^+)$ and $\phi^- := (\phi_0^-, \phi_\infty^-)$, where*

$$\begin{aligned} \phi_0^+ &:= (h_1\phi_0) \circ C_\tau, & \phi_\infty^+ &:= (h_0\phi_\infty) \circ C_\tau, \\ \phi_0^- &:= (h_0\phi_0) \circ C_\tau, & \phi_\infty^- &:= (h_1\phi_\infty) \circ C_\tau, \end{aligned} \quad (4.4)$$

belong to $\tilde{\mathcal{D}}'(\overline{\mathbb{R}})$. Their action on $C^\infty(\overline{\mathbb{R}})$ as linear functionals is given by

$$\phi^+(f) = \phi(h_1 C_\tau(f)), \quad \phi^-(f) = \phi(h_0 C_\tau(f)), \quad f \in C^\infty(\overline{\mathbb{R}}), \quad (4.5)$$

and we have $\text{supp } \phi^\pm \subseteq [0, \infty) \cup \{\infty\}$.

Proof. As we noticed before the lemma, the components of ϕ^+ and ϕ^- are distributions on \mathbb{R} . We have to check the transformation law (2.1). To this end, let $f \in \mathcal{D}(\mathbb{R})$ with $0 \notin \text{supp } f$ be given. Then, with (4.3), we have

$$\begin{aligned}\phi_0^+(f \circ \Lambda_\infty) &= (h_1 \phi_0)[f \circ \Lambda_\infty \circ \tau] = \phi_0[h_1 \cdot (f \circ \tau \circ \Lambda_\infty)] \\ &= \phi_0[(h_0 \cdot (f \circ \tau)) \circ \Lambda_\infty] = \phi_\infty[h_0 \cdot (f \circ \tau)] \\ &= (h_0 \phi_\infty)[f \circ \tau] = \phi_\infty^+(f).\end{aligned}$$

The validity of the transformation law for ϕ^- is seen in the same way.

For the proof of (4.5), choose a partition of unity $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ subordinate to the open cover $\{\mathbb{R} \setminus \{\infty\}, \mathbb{R} \setminus \{0\}\}$. Set $\tilde{\chi}^0 = \chi^0 \circ \tau, \tilde{\chi}^\infty = \chi^\infty \circ \tau$. Then $\tilde{\chi}^0, \tilde{\chi}^\infty \in C^\infty(\overline{\mathbb{R}})$ is a partition of unity subordinate to the same open cover. This, together with

$$\begin{aligned}\phi_0^+(\chi^0 f) &= (h_1 \phi_0)[(\chi^0 \circ \tau) \cdot (f \circ \tau)] = \phi_0[h_1 \cdot \tilde{\chi}^0 \cdot (f \circ \tau)], \\ \phi_\infty^+(\chi^\infty f \circ \Lambda_\infty^{-1}) &= (h_0 \phi_\infty)[(\chi^\infty f) \circ \Lambda_\infty^{-1} \circ \tau] = (h_0 \phi_\infty)[(\chi^\infty f) \circ \tau \circ \Lambda_\infty^{-1}] \\ &= (h_0 \phi_\infty)[(\tilde{\chi}^\infty \cdot (f \circ \tau)) \circ \Lambda_\infty^{-1}] = \phi_\infty[h_0 \cdot ((\tilde{\chi}^\infty \cdot (f \circ \tau)) \circ \Lambda_\infty^{-1})] \\ &= \phi_\infty[(h_1 \cdot \tilde{\chi}^\infty \cdot (f \circ \tau)) \circ \Lambda_\infty^{-1}],\end{aligned}$$

yields

$$\begin{aligned}\phi^+(f) &= \phi_0^+(\chi^0 f) + \phi_\infty^+(\chi^\infty f \circ \Lambda_\infty^{-1}) \\ &= \phi_0[\tilde{\chi}^0 \cdot h_1 \cdot (f \circ \tau)] + \phi_\infty[(\tilde{\chi}^\infty \cdot h_1 \cdot (f \circ \tau)) \circ \Lambda_\infty^{-1}] = \phi[h_1 \cdot (f \circ \tau)].\end{aligned}$$

The second relation in (4.5) is seen in the same way.

If $\text{supp } f \subseteq (-\infty, 0)$, then $C_\tau(f)$ vanishes identically, and hence $\phi^\pm(f) = 0$. This implies that $\text{supp } \phi^\pm \subseteq [0, \infty) \cup \{\infty\}$. \square

In the next lemma we consider the case when ϕ belongs to the class $\mathcal{F}_{\{\infty\}}$ and relate the corresponding measures.

4.3 Lemma. *Let $\phi \in \mathcal{F}_{\{\infty\}}$. Then also $\phi^+, \phi^- \in \mathcal{F}_{\{\infty\}}$, and the measures μ_ϕ, μ_{ϕ^+} and μ_{ϕ^-} are related as follows ($\tau: \mathbb{R} \rightarrow \mathbb{R}$ denotes again the map $\tau(t) := t^2$ and μ_ϕ^τ the corresponding image measure):*

$$\mu_{\phi^+} \ll \mu_\phi^\tau, \quad \frac{d\mu_{\phi^+}}{d\mu_\phi^\tau}(t) = t \cdot \mathbf{1}_{(0, \infty)}, \quad (4.6)$$

$$\mu_{\phi^-} \ll \mu_\phi^\tau, \quad \frac{d\mu_{\phi^-}}{d\mu_\phi^\tau}(t) = \mathbf{1}_{[0, \infty)}, \quad (4.7)$$

where, e.g. $\mathbf{1}_{(0, \infty)}$ denotes the characteristic function of $(0, \infty)$.

Assume, in addition, that μ_ϕ is absolutely continuous with respect to the Lebesgue measure λ on some interval (a, b) with $0 \leq a < b$. Then μ_{ϕ^+} and μ_{ϕ^-} are absolutely continuous with respect to λ on the interval (a^2, b^2) , and

$$\begin{aligned}\frac{d\mu_{\phi^+}}{d\lambda}(t) &= \sqrt{t} \frac{d\mu_\phi}{d\lambda}(\sqrt{t}), \\ \frac{d\mu_{\phi^-}}{d\lambda}(t) &= \frac{1}{\sqrt{t}} \cdot \frac{d\mu_\phi}{d\lambda}(\sqrt{t}),\end{aligned} \quad t \in (a^2, b^2). \quad (4.8)$$

Proof. Write $\phi = (\phi_0, \phi_\infty)$ and let $f \in \mathcal{D}(\mathbb{R})$. Then

$$\begin{aligned}\phi_0^+(f) &= \phi_0(h_1 \cdot (f \circ \tau)) = \int_{\mathbb{R}} h_1(s) f(s^2) \frac{d\mu_\phi(s)}{1+s^2} \\ &= \int_{\mathbb{R}} \frac{s^2}{1+s^4} f(s^2) d\mu_\phi(s) = \int_{\tau(\mathbb{R})} \frac{t}{1+t^2} f(t) d\mu_\phi^\tau(t) \\ &= \int_{\mathbb{R}} f(t) \cdot \frac{t \cdot \mathbf{1}_{(0,\infty)} \cdot d\mu_\phi^\tau(t)}{1+t^2},\end{aligned}$$

and

$$\begin{aligned}\phi_0^-(f) &= \phi_0(h_0 \cdot (f \circ \tau)) = \int_{\mathbb{R}} h_0(s) f(s^2) \frac{d\mu_\phi(s)}{1+s^2} \\ &= \int_{\mathbb{R}} \frac{1}{1+s^4} f(s^2) d\mu_\phi(s) = \int_{\tau(\mathbb{R})} \frac{1}{1+t^2} f(t) d\mu_\phi^\tau(t) \\ &= \int_{\mathbb{R}} f(t) \cdot \frac{\mathbf{1}_{[0,\infty)} \cdot d\mu_\phi^\tau(t)}{1+t^2}.\end{aligned}$$

Assume now that μ_ϕ is absolutely continuous with respect to λ on (a, b) where $0 \leq a < b$. Let c, d be arbitrary such that $a \leq c < d \leq b$. It follows from (4.6) that

$$\begin{aligned}\mu_{\phi^+}((c, d)) &= \int_{(c,d)} t d\mu_\phi^\tau(t) = \int_{\tau^{-1}((c,d))} s^2 d\mu_\phi(s) \\ &= 2 \int_{(\sqrt{c}, \sqrt{d})} s^2 d\mu_\phi(s) = 2 \int_{(\sqrt{c}, \sqrt{d})} s^2 \frac{d\mu_\phi}{d\lambda}(s) ds \\ &= 2 \int_{(c,d)} t \frac{d\mu_\phi}{d\lambda}(\sqrt{t}) \frac{dt}{2\sqrt{t}} = \int_{(c,d)} \sqrt{t} \frac{d\mu_\phi}{d\lambda}(\sqrt{t}) dt,\end{aligned}$$

which implies the first relation in (4.8). The second relation is shown in a similar way. \square

Let us note explicitly that, in the situation of the above lemma, $\text{supp } \mu_\phi^\tau \subseteq [0, \infty)$. Hence, we could also write $d\mu_{\phi^+}(s) = s d\mu_\phi^\tau(s)$ and $\mu_{\phi^-} = \mu_\phi^\tau$.

The next theorem provides the distributional representations for the functions q_\pm in terms of the representation of a function q from the class $\mathcal{N}_{<\infty}$.

4.4 Theorem. *Let $q \in \mathcal{N}_{<\infty}$ be symmetric and let $q(z) = r(z) + \phi(\beta_z)$ with $r \in \mathbb{R}(z)$ and $\phi \in \tilde{\mathcal{D}}'(\overline{\mathbb{R}})$ be its distributional representation (3.2). Moreover, let q_+ and q_- be the functions defined in Lemma 4.2. Then the unique distributional representations of q_+ and q_- are*

$$q_+(\lambda) = r^+(\lambda) + \phi^+(\beta_\lambda), \quad q_-(\lambda) = r^-(\lambda) + \phi^-(\beta_\lambda)$$

where ϕ^+ and ϕ^- are defined as in (4.4) and (with h_0 as in (4.2))

$$r^+(\lambda) := \sqrt{\lambda} r(\sqrt{\lambda}) - \phi(h_0), \quad r^-(\lambda) := \frac{r(\sqrt{\lambda})}{\sqrt{\lambda}} + \phi(h_0).$$

Assume in addition that $q \in \mathcal{N}_{<\infty}^{(\infty)}$. Then $q_+, q_- \in \mathcal{N}_{<\infty}^{(\infty)}$, and the corresponding measures satisfy

$$\frac{d\mu_{q_+}}{d\mu_q^\tau}(t) = t \cdot \mathbb{1}_{(0, \infty)}, \quad \frac{d\mu_{q_-}}{d\mu_q^\tau}(t) = \mathbb{1}_{[0, \infty)}, \quad (4.9)$$

where $\tau : \mathbb{R} \rightarrow \mathbb{R}$ denotes again the map $\tau(t) := t^2$ and μ_q^τ the corresponding image measure of μ_q .

Proof. Set $\hat{\beta}_z(t) := \beta_z(-t)$. Since ϕ is symmetric, we have $\phi(\beta_z) = \phi(\hat{\beta}_z)$. Hence, we may express q_+ as follows

$$q_+(z^2) = zq(z) = zr(z) + \frac{z}{2} \left(\phi(\beta_z) + \phi(\hat{\beta}_z) \right) = zr(z) + \phi\left(\frac{z}{2}(\beta_z + \hat{\beta}_z)\right).$$

For $t \in \mathbb{R}$ we have

$$\begin{aligned} \frac{z}{2}(\beta_z(t) + \hat{\beta}_z(t)) &= \frac{z}{2} \left(\frac{1+tz}{t-z} + \frac{1-tz}{-t-z} \right) = \frac{z^2(1+t^2)}{t^2-z^2} \\ &= \frac{t^2(1+t^2)}{1+t^4} \beta_{z^2}(t^2) - \frac{1+t^2}{1+t^4} = h_1(t)C_\tau(\beta_{z^2})(t) - h_0(t), \end{aligned}$$

and this relation extends also to $t = \infty$. Hence

$$q_+(z^2) = zr(z) + \phi(h_1C_\tau(\beta_{z^2})) - \phi(h_0) = [zr(z) - \phi(h_0)] + \phi^+(\beta_{z^2}),$$

which shows the required representation of q_+ . The representation of q_- is proved in the same way.

Note that the function $\sqrt{\lambda}r(\sqrt{\lambda})$ is rational and symmetric with respect to \mathbb{R} since r is rational, symmetric with respect to \mathbb{R} and odd. Moreover, we have $r(z) = O(\frac{1}{z})$ when $|z| \rightarrow \infty$, and hence the function $\sqrt{\lambda}r(\sqrt{\lambda})$ remains bounded at infinity.

If $q \in \mathcal{N}_{<\infty}^{(\infty)}$, then r must vanish identically (as an odd and constant function), and $\phi \in \mathcal{F}_{\{\infty\}}$. Thus also ϕ^+ and ϕ^- belong to $\mathcal{F}_{\{\infty\}}$ by Lemma 4.3, and the corresponding rational summands in the representations of q_+ and q_- are constant. This shows that q_+ and q_- belong to $\mathcal{N}_{<\infty}^{(\infty)}$. The relations in (4.9) follow directly from (4.6) and (4.7). \square

5 The operator model associated with $\phi \in \mathcal{F}_{\{\infty\}}$

With a distributional density $\phi \in \mathcal{F}(\overline{\mathbb{R}})$ a model space and an operator are associated; see [24], [27]. Let us recall the definitions for the present case of interest, that is, for $\phi \in \mathcal{F}_{\{\infty\}}$.

We denote by $\mathcal{B}_p(\phi)$, $p \in [1, \infty)$, the linear space of all complex-valued functions f on \mathbb{R} for which there exists a $T > 0$ such that

$$f|_{\overline{\mathbb{R}} \setminus [-T, T]} \in C^\infty(\overline{\mathbb{R}} \setminus [-T, T]) \quad \text{and} \quad f|_{(-2T, 2T)} \in L^p\left(\frac{d\mu_\phi(x)}{1+x^2}\right).$$

The action of a distributional density $\phi \in \mathcal{F}_{\{\infty\}}$ extends naturally from $C^\infty(\overline{\mathbb{R}})$ to $\mathcal{B}_1(\phi)$. Namely, if $f \in \mathcal{B}_1(\phi)$, choose $T > 0$ as above and a partition of unity $\chi^0, \chi^\infty \in C^\infty(\overline{\mathbb{R}})$ subordinate to the open cover $\{(-2T, 2T), \overline{\mathbb{R}} \setminus [-T, T]\}$. Then

$$\phi(f) := \int_{(-2T, 2T)} \chi^0(x) f(x) \frac{d\mu_\phi(x)}{1+x^2} + \phi_\infty((\chi^\infty f) \circ \Lambda_\infty^{-1})$$

is well defined, does not depend on the partition of unity, and ϕ is a linear functional on $\mathcal{B}_1(\phi)$.

5.1 Definition. Let $\phi \in \mathcal{F}_{\{\infty\}}$ be given. Then we define an inner product $[\cdot, \cdot]_\phi$ on $\mathcal{B}_2(\phi)$ by

$$[f, g]_\phi := \phi(f\bar{g}), \quad f, g \in \mathcal{B}_2(\phi).$$

The Pontryagin space completion of the inner product space $\langle \mathcal{B}_2(\phi), [\cdot, \cdot]_\phi \rangle$ (which exists as shown in the references named above) is the model space associated with ϕ and is denoted by $\Pi(\phi)$.

The linear relation

$$A_\phi := \text{Clos} \{ (f; g) \in \mathcal{B}_2(\phi)^2 : g(t) = tf(t), t \in \mathbb{R} \}$$

is the model relation associated with ϕ . Here ‘‘Clos’’ denotes the closure in $\Pi(\phi) \times \Pi(\phi)$. \diamond

It was shown in [27, Proposition 3.1] that A_ϕ is self-adjoint and has non-empty resolvent set. Moreover, the point ∞ is the only possible critical point of A_ϕ and, at the same time, the only possible point of non-positive type of A_ϕ .

We denote by $\text{mul}(A_\phi^n)$ the multi-valued part of the relation A_ϕ^n and set

$$\mathcal{E}_{A_\phi}(\infty) := \bigcup_{n=1}^{\infty} \text{mul}(A_\phi^n) \subseteq \Pi(\phi).$$

5.2 Remark. Let $\phi \in \mathcal{F}_{\{\infty\}}$ and denote by $\mathcal{E}_{A_\phi}(\infty)^\circ$ the isotropic part of $\mathcal{E}_{A_\phi}(\infty)$. Then

$$\dim(\mathcal{E}_{A_\phi}(\infty)^\circ) = \Delta(\mu_\phi). \quad (5.1)$$

In particular, we see that the point ∞ is a singular critical point of A_ϕ if and only if $\Delta(\mu_\phi) > 0$.

This follows from the explicit form of the model operator given in [24, §3.2] using the transformation ‘‘Inv’’ from [27, §2] to exchange the roles of 0 and ∞ . Relation (5.1) can also be deduced from the Stieltjes inversion formula (3.7) and [10, Theorem 4.2], where it was shown that the minimal possible m in (3.5) is equal to $\dim(\mathcal{E}_{A_\phi}(\infty)^\circ)$. \diamond

It is an important fact that the model relation A_ϕ is closely related to the multiplication operator M_x in the space $L^2((1+x^2)^{-1}d\mu_\phi(x))$; the next theorem contains the precise statement. Its proof is not difficult, given the knowledge from [27, Proposition 3.1].

5.3 Theorem. *Let $\phi \in \mathcal{F}_{\{\infty\}}$ be given. Then the map*

$$\text{id} : \{ f \in \mathcal{B}_2(\phi) : \text{supp } f \subseteq \mathbb{R} \} \rightarrow L^2\left(\frac{d\mu_\phi(x)}{1+x^2}\right)$$

extends to an isometric, continuous and surjective map

$$\psi(\phi) : \mathcal{E}_{A_\phi}(\infty)^\perp \rightarrow L^2\left(\frac{d\mu_\phi(x)}{1+x^2}\right).$$

Moreover,

$$(\psi(\phi) \times \psi(\phi))(A_\phi \cap (\mathcal{E}_{A_\phi}(\infty)^\perp)^2) = M_x$$

where M_x denotes the graph of the operator of multiplication by the independent variable.

Proof. Set

$$\begin{aligned}\mathcal{L}_N &:= \{f \in \mathcal{B}_2(\phi) : \text{supp } f \subseteq [-N, N]\}, \quad N \in \mathbb{N}, \\ \mathcal{L} &:= \bigcup_{N \in \mathbb{N}} \mathcal{L}_N, \quad \mathcal{A} := \text{Clos } \mathcal{L}.\end{aligned}$$

It follows from the definitions of the inner product in $\mathcal{B}_2(\phi)$ and the measure μ_ϕ that the identity maps \mathcal{L} isometrically onto a dense subspace of $L^2((1+x^2)^{-1}d\mu_\phi(x))$. It therefore extends to a continuous, isometric and surjective map from \mathcal{A} onto $L^2((1+x^2)^{-1}d\mu_\phi(x))$, cf. [37, Proposition 2.1]; we denote this extension by $\psi(\phi)$.

Denote by E the spectral family associated with A_ϕ ; see, e.g. [33]. Since the only possible critical point of A_ϕ and the only possible point of non-positive type of A_ϕ is ∞ , the spectral projector $E(\Delta)$ is defined for every bounded Borel set. The space \mathcal{L}_N is complete with respect to $[\cdot, \cdot]_\phi$ and hence a closed subspace of $\Pi(\phi)$. By [27, Proposition 3.1] we have $E([-N, N])f = \mathbb{1}_{[-N, N]} \cdot f$, $f \in \mathcal{B}_2(\phi)$, where $\mathbb{1}_{[-N, N]}$ denotes the characteristic function of $[-N, N]$. Hence $E([-N, N])\mathcal{B}_2(\phi) = \mathcal{L}_N$. Since \mathcal{L}_N is closed, it follows that $\text{ran } E([-N, N]) = \mathcal{L}_N$. We conclude that

$$\mathcal{L} = \bigcup_{N \in \mathbb{N}} \text{ran } E([-N, N]),$$

and hence that $\mathcal{A} = \mathcal{E}_{A_\phi}(\infty)^\perp$. This shows the first assertion.

Denote by $M_x^{(N)}$ the multiplication operator in the space \mathcal{L}_N , which clearly has non-empty resolvent set and satisfies $A_\phi \cap \mathcal{L}_N^2 \supseteq M_x^{(N)}$. Since each space \mathcal{L}_N is invariant under resolvents of A_ϕ , also $A_\phi \cap \mathcal{L}_N^2$ has non-empty resolvent set, and hence

$$A_\phi \cap \mathcal{L}_N^2 = M_x^{(N)}.$$

Again, since \mathcal{L}_N is invariant under resolvents of A_ϕ , we have

$$(\psi(\phi) \times \psi(\phi))(A_\phi \cap \mathcal{A}^2) = \text{Clos} \left(\bigcup_{N \in \mathbb{N}} (\psi(\phi) \times \psi(\phi))(A_\phi \cap \mathcal{L}_N^2) \right).$$

Here the closure is taken in $L^2((1+x^2)^{-1}d\mu_\phi(x))$. As we have seen above, the right-hand side of the above relation is further equal to

$$\text{Clos} \left(\bigcup_{N \in \mathbb{N}} M_x^{(N)} \right) = M_x,$$

and the second assertion follows. \square

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