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A NOTE ON NEW CLASSES OF INFINITELY DIVISIBLE DISTRIBUTIONS ON $\mathbb{R}^d$

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Abstract
This paper introduces and studies a family of new classes of infinitely divisible distributions on $\mathbb{R}^d$ with two parameters. Depending on parameters, these classes connect the Goldie–Steutel–Bondesson class and the class of generalized type G distributions, connect the Thorin class and the class M, and connect the class M and the class of generalized type G distributions. These classes are characterized by stochastic integral representations with respect to Lévy processes.

1 Introduction

Let $I(\mathbb{R}^d)$ be the class of all infinitely divisible distributions on $\mathbb{R}^d$. $\widehat{\mu}(z), z \in \mathbb{R}^d$, denotes the characteristic function of $\mu \in I(\mathbb{R}^d)$ and $|x|$ denotes the Euclidean norm of $x \in \mathbb{R}^d$. We use the Lévy-Khintchine triplet (A, ν, γ) of $\mu \in I(\mathbb{R}^d)$ in the sense that

$$\widehat{\mu}(z) = \exp\left\{-2^{-1}\langle z, Az\rangle + \mathrm{i}\langle \gamma, z\rangle + \int_{\mathbb{R}^d} \left(e^{\mathrm{i}\langle z,x\rangle} - 1 - \mathrm{i}\langle z, x\rangle (1+|x|^2)^{-1}\right) \nu(dx)\right\}, \quad z \in \mathbb{R}^d,$$

where A is a symmetric nonnegative-definite $d \times d$ matrix, $\gamma \in \mathbb{R}^d$ and ν is a measure (called the Lévy measure) on $\mathbb{R}^d$ satisfying

$$\nu(\{0\}) = 0 \text{ and } \int_{\mathbb{R}^d} (|x|^2 \wedge 1)\nu(dx) < \infty.$$

The following polar decomposition is a basic result on the Lévy measure of $\mu \in I(\mathbb{R}^d)$. Let ν be the Lévy measure of some $\mu \in I(\mathbb{R}^d)$ with $0 < \nu(\mathbb{R}^d) \le \infty$. Then there exist a measure λ on

$S=\{x\in\mathbb{R}^d : |x|=1\}$ with $0<\lambda(S)\le\infty$ and a family $\{\nu_\xi\colon \xi\in S\}$ of measures on $(0,\infty)$ such that $\nu_\xi(B)$ is measurable in ξ for each $B\in\mathscr{B}((0,\infty))$, $0<\nu_\xi((0,\infty))\le\infty$ for each $\xi\in S$, and

$$\nu(B)=\int_S \lambda(d\xi)\int_0^\infty 1_B(r\xi)\nu_\xi(dr),\ B\in\mathscr{B}(\mathbb{R}^d\setminus\{0\}). \tag{1.1}$$

Here λ and $\{\nu_\xi\}$ are uniquely determined by ν up to multiplication of measurable functions $c(\xi)$ and $\frac{1}{c(\xi)}$, respectively, with $0<c(\xi)<\infty$. We say that ν has the polar decomposition (λ,ν_ξ) and ν_ξ is called the radial component of ν. (See, e.g., Barndorff-Nielsen et al. (2006), Lemma 2.1.)
A real-valued function f defined on $(0,\infty)$ is said to be completely monotone if it has derivatives $f^{(n)}$ of all orders and for each $n=0,1,2,...$, $(-1)^n f^{(n)}(r)\ge 0, r>0$. Bernstein's theorem says that f on $(0,\infty)$ is completely monotone if and only if there exists a (not necessarily finite) measure Q on $[0,\infty)$ such that $f(r)=\int_{[0,\infty)}e^{-ru}Q(du)$. (See, e.g., Feller (1966), p.439.)
In this paper, we introduce and study the following classes.

Definition 1.1. *(The class $J_{\alpha,\beta}(\mathbb{R}^d)$.) Let $\alpha<2$ and $\beta>0$. We say that $\mu\in I(\mathbb{R}^d)$ belongs to the class $J_{\alpha,\beta}(\mathbb{R}^d)$ if $\nu=0$ or $\nu\ne 0$ and, in case $\nu\ne 0$, ν_ξ in (1.1) has expression*

$$\nu_\xi(dr)=r^{-\alpha-1}g_\xi(r^\beta)dr,\ r>0, \tag{1.2}$$

where $g_\xi(x)$ is measurable in ξ, is completely monotone in x on $(0,\infty)$ λ-a.e. ξ, not identically zero and $\lim_{x\to\infty}g_\xi(x)=0$ λ-a.e. ξ.

Remark 1.2. *If $\alpha\le 0$, then automatically $\lim_{x\to\infty}g_\xi(x)=0$ λ-a.e. ξ, because of the finiteness of $\int_{|x|>1}\nu(dx)$. So, when we consider the classes $B(\mathbb{R}^d), G(\mathbb{R}^d), T(\mathbb{R}^d)$ and $M(\mathbb{R}^d)$ appearing later, we do not have to write this condition explicitly.*

Remark 1.3. *The integrability condition of the Lévy measure $\int_{\mathbb{R}^d}(|x|^2\wedge 1)\nu(dx)<\infty$ implies that*

$$\int_0^\infty (r^2\wedge 1)r^{-\alpha-1}g_\xi(r^\beta)dr<\infty,\ \lambda\text{-a.e. } \xi, \tag{1.3}$$

so we do not have to assume (1.3) in the definition. It is automatically satisfied.

Remark 1.4. *The classes $J_{\alpha,1}(\mathbb{R}^d), \alpha<2$, are studied in Sato (2006b).*

Before mentioning our motivation of this study, we state a general result on the relations among the classes $J_{\alpha,\beta}(\mathbb{R}^d), \alpha<2, \beta>0$.

Theorem 1.5. (i) *Fix $\alpha<2$ and let $0<\beta_1<\beta_2$. Then*

$$J_{\alpha,\beta_1}(\mathbb{R}^d)\subset J_{\alpha,\beta_2}(\mathbb{R}^d).$$

(ii) *Fix $\beta>0$ and let $\alpha_1<\alpha_2<2$. Then*

$$J_{\alpha_2,\beta}(\mathbb{R}^d)\subset J_{\alpha_1,\beta}(\mathbb{R}^d).$$

Proof. For the proof of (i), we need the following lemma.

Lemma 1.6. (See Feller (1966), p.441, Corollary 2.) *Let ϕ be a completely monotone function on $(0,\infty)$ and let ψ be a nonnegative function on $(0,\infty)$ whose derivative is completely monotone. Then $\phi(\psi)$ is completely monotone.*

Let $h_\xi(x) = g_\xi(x^{\beta_1/\beta_2}), x > 0$, where g_ξ is the one in (1.2), which is completely monotone on $(0,\infty)$. Since $\psi(x) = x^{\beta_1/\beta_2}, x > 0$, has a completely monotone derivative, it follows from Lemma 1.6 that $h_\xi(x)$ is completely monotone. Suppose $\mu \in J_{\alpha,\beta_1}(\mathbb{R}^d)$ and let g_ξ be the one in (1.2). Since $g_\xi(r^{\beta_1}) = h_\xi(r^{\beta_2})$, where h_ξ is completely monotone as has been just shown above, we have $\mu \in J_{\alpha,\beta_2}(\mathbb{R}^d)$. This proves (i).
To prove (ii), suppose that $\mu \in J_{\alpha_2,\beta}(\mathbb{R}^d)$. Then $\nu_\xi(dr) = r^{-\alpha_2-1}g_\xi(r^\beta)dr,\ r > 0$, as in (1.2), where g_ξ is completely monotone on $(0,\infty)$ λ-a.e. ξ. Note that

$$h_\xi(x) = x^{-(\alpha_2-\alpha_1)/\beta} g_\xi(x)$$

is completely monotone, because $x^{-p}, p > 0$, is completely monotone and the product of two completely monotone functions is also completely monotone. We now have

$$\nu_\xi(dr) = r^{-\alpha_2-1}g_\xi(r^\beta)dr = r^{-\alpha_1-1}h_\xi(r^\beta)dr,$$

and thus μ also belongs to $J_{\alpha_1,\beta}(\mathbb{R}^d)$. This proves (ii). $\square$

The motivations for studying the classes $J_{\alpha,\beta}(\mathbb{R}^d)$ are the following.

I. The classes connecting the Goldie–Steutel–Bondesson class and the class of generalized type G distributions.

Let $\alpha = -1$ and consider the classes $J_{-1,\beta}(\mathbb{R}^d)$, $\beta > 0$. A distribution $\mu \in I(\mathbb{R}^d)$ is said to be of generalized type G if ν_ξ in (1.2) has expression $\nu_\xi(dr) = g_\xi(r^2)dr$ for some completely monotone function g_ξ on $(0,\infty)$, and denote by $G(\mathbb{R}^d)$ the class of all generalized type G distributions on $\mathbb{R}^d$. Let $I_{\text{sym}}(\mathbb{R}^d) = \{\mu \in I(\mathbb{R}^d)\ :\ \mu \text{ is symmetric in the sense that } \mu(B) = \mu(-B), B \in \mathscr{B}(\mathbb{R}^d)\}$.

Remark 1.7. *A distribution $\mu \in G(\mathbb{R}^d) \cap I_{\text{sym}}(\mathbb{R}^d)$ is a so-called type G distribution, which is, in one dimension, a variance mixture of the standard normal distribution with a positive infinitely divisible mixing distribution.*

Remark 1.8. $G(\mathbb{R}^d) = J_{-1,2}(\mathbb{R}^d)$.

Remark 1.9. *The Goldie-Steutel-Bondesson class denoted by $B(\mathbb{R}^d)$ is $J_{-1,1}(\mathbb{R}^d)$. (For details on $B(\mathbb{R}^d)$, see Barndorff-Nielsen et al. (2006).)*

Therefore, by Theorem 1.5 (i) with $\alpha = -1$, for $1 < \beta < 2$,

$$B(\mathbb{R}^d) \subset J_{-1,\beta}(\mathbb{R}^d) \subset G(\mathbb{R}^d),$$

and hence $\{J_{-1,\beta}(\mathbb{R}^d), 1 \le \beta \le 2\}$ is a family of classes of infinitely divisible distributions on $\mathbb{R}^d$ connecting $B(\mathbb{R}^d)$ and $G(\mathbb{R}^d)$ with continuous parameter $\beta \in [1,2]$.

II. The classes connecting the Thorin class and the class $M(\mathbb{R}^d)$.

Let $\alpha = 0$ and consider the classes $J_{0,\beta}(\mathbb{R}^d)$, $\beta > 0$.

Remark 1.10. *The Thorin class denoted by $T(\mathbb{R}^d)$ is $J_{0,1}(\mathbb{R}^d)$. (For details on $T(\mathbb{R}^d)$, see also Barndorff-Nielsen et al. (2006).)*

Remark 1.11. *The class $M(\mathbb{R}^d)$ is defined by $J_{0,2}(\mathbb{R}^d)$. (The class $M(\mathbb{R}^d) \cap I_{\text{sym}}(\mathbb{R}^d)$ is studied in Aoyama et al. (2008).)*

By Theorem 1.5 (i) with $\alpha = 0$, for $1 < \beta < 2$,

$$T(\mathbb{R}^d) \subset J_{0,\beta}(\mathbb{R}^d) \subset M(\mathbb{R}^d),$$

and hence $\{J_{0,\beta}(\mathbb{R}^d), 1 \le \beta \le 2\}$ is a family of classes of infinitely divisible distributions on $\mathbb{R}^d$ connecting $T(\mathbb{R}^d)$ and $M(\mathbb{R}^d)$ with continuous parameter $\beta \in [1, 2]$.

III. The classes connecting the classes $M(\mathbb{R}^d)$ and $G(\mathbb{R}^d)$.

Let $\beta = 2$ and consider the classes $J_{\alpha,2}(\mathbb{R}^d)$, $\alpha < 2$. Then, by Theorem 1.5 (ii) with $\beta = 2$, for $-1 \le \alpha \le 0$

$$M(\mathbb{R}^d) \subset J_{\alpha,2}(\mathbb{R}^d) \subset G(\mathbb{R}^d),$$

and hence $\{J_{\alpha,2}(\mathbb{R}^d), -1 \le \alpha \le 0\}$ is a family of classes of infinitely divisible distributions on $\mathbb{R}^d$ connecting $M(\mathbb{R}^d)$ and $G(\mathbb{R}^d)$ with continuous parameter $\alpha \in [-1, 0]$.

IV. The classes connecting the classes $T(\mathbb{R}^d)$ and $B(\mathbb{R}^d)$.

Let $\beta = 1$ and consider the classes $J_{\alpha,1}(\mathbb{R}^d)$, $\alpha < 2$. Then, by Theorem 1.5 (ii) with $\beta = 1$, for $-1 \le \alpha \le 0$

$$T(\mathbb{R}^d) \subset J_{\alpha,1}(\mathbb{R}^d) \subset B(\mathbb{R}^d),$$

and hence $\{J_{\alpha,1}(\mathbb{R}^d), -1 \le \alpha \le 0\}$ is a family of classes of infinitely divisible distributions on $\mathbb{R}^d$ connecting $T(\mathbb{R}^d)$ and $B(\mathbb{R}^d)$ with continuous parameter $\alpha \in [-1, 0]$. (This fact is already mentioned in Sato (2006b).)

2 Stochastic integral characterizations for $J_{\alpha,\beta}(\mathbb{R}^d)$

The purpose of this paper is to characterize the classes $J_{\alpha,\beta}(\mathbb{R}^d)$ by stochastic integral representations. For that, we first define mappings from $I(\mathbb{R}^d)$ into $I(\mathbb{R}^d)$ and investigate the domains of those mappings.
We introduce the following function $G_{\alpha,\beta}(u)$. For $\alpha < 2$ and $\beta > 0$, let

$$G_{\alpha,\beta}(u) = \int_u^\infty x^{-\alpha-1} e^{-x^\beta} dx, \quad u \ge 0,$$

and let $G^*_{\alpha,\beta}(t)$ be the inverse function of $G_{\alpha,\beta}(u)$, that is, $t = G_{\alpha,\beta}(u)$ if and only if $u = G^*_{\alpha,\beta}(t)$. Let $\{X_t^{(\mu)}\}$ be a Lévy process on $\mathbb{R}^d$ with the law $\mu \in I(\mathbb{R}^d)$ at $t = 1$. We consider the stochastic integrals

$$\int_0^{G_{\alpha,\beta}(0)} G^*_{\alpha,\beta}(t) dX_t^{(\mu)}, \quad \text{where} \quad G_{\alpha,\beta}(0) = \begin{cases} \beta^{-1}\Gamma(-\alpha\beta^{-1}), & \text{if } \alpha < 0, \\ \infty, & \text{if } \alpha \ge 0. \end{cases}$$

As to the definition of stochastic integrals of non-random measurable functions f which are $\int_0^T f(t) dX_t^{(\mu)}, T < \infty, \mu \in I(\mathbb{R}^d)$, we follow the definition in Sato (2004, 2006a), whose idea is to define a stochastic integral with respect to $\mathbb{R}^d$-valued independently scatted random measure induced by a Lévy process on $\mathbb{R}^d$. The improper stochastic integral $\int_0^\infty f(t) dX_t^{(\mu)}$ is defined as the limit in probability of $\int_0^T f(t)dX_t^{(\mu)}$ as $T \to \infty$ whenever the limit exists. See also Sato (2006b). In the following, $\mathscr{L}(X)$ stands for "the law of X". If we write

$$\Psi_{\alpha,\beta}(\mu) = \mathscr{L}\left(\int_0^{G_{\alpha,\beta}(0)} G^*_{\alpha,\beta}(t)dX_t^{(\mu)}\right),$$

then $\Psi_{\alpha,\beta}$ can be considered as a mapping with domain $\mathfrak{D}(\Psi_{\alpha,\beta})$ being the class of $\mu \in I(\mathbb{R}^d)$ for which $\int_0^{G_{\alpha,\beta}(0)} G^*_{\alpha,\beta}(t)dX_t^{(\mu)}$ is definable.

Theorem 2.1. *If $\alpha < 0$, then $\mathfrak{D}(\Psi_{\alpha,\beta}) = I(\mathbb{R}^d)$.*

Proof. By Proposition 3.4 in Sato (2006a), since $G_{\alpha,\beta}(0) < \infty$ for $\alpha < 0$, if $\int_0^{G_{\alpha,\beta}(0)} \left(G^*_{\alpha,\beta}(t)\right)^2 dt < \infty$, then $\int_0^{G_{\alpha,\beta}(0)} G^*_{\alpha,\beta}(t)dX_t^{(\mu)}$ is well-defined. Actually,

$$\int_0^{G_{\alpha,\beta}(0)} \left(G^*_{\alpha,\beta}(t)\right)^2 dt = -\int_0^\infty u^2 dG_{\alpha,\beta}(u) = \int_0^\infty u^{1-\alpha}e^{-u^\beta}du < \infty.$$

□

To determine the domain of $\Psi_{\alpha,\beta}, \alpha \geq 0$, we need the following result by Sato (2006b). In the following, $a(t) \sim b(t)$ means that $\lim_{t\to\infty} a(t)/b(t) = 1$, $a(t) \asymp b(t)$ means that $0 < \liminf_{t\to\infty} a(t)/b(t) \leq \limsup_{t\to\infty} a(t)/b(t) < \infty$ and $I_{\log}(\mathbb{R}^d) = \{\mu \in I(\mathbb{R}^d) : \int_{\mathbb{R}^d} \log^+|x|\mu(dx) < \infty\}$, where $\log^+|x| = (\log|x|) \vee 0$.

Proposition 2.2. (Sato (2006b), Theorems 2.4 and 2.8.) *Let $p \geq 0$. Denote*

$$\Phi_{\varphi_p}(\mu) = \mathscr{L}\left(\int_0^\infty \varphi_p(t)dX_t^{(\mu)}\right).$$

Suppose that φ_p is locally square-integrable with respect to Lebesgue measure on $[0,\infty)$ and satisfies
(1) $\varphi_0(t) \asymp e^{-ct}$ as $t \to \infty$ with some $c > 0$,
(2) $\varphi_p(t) \asymp t^{-1/p}$ as $t \to \infty$ for $p \in (0,1) \cup (1,\infty)$,
(3) $\varphi_1(t) \asymp t^{-1}$ as $t \to \infty$ and for some $t_0 > 0, c > 0$ and $\psi(t), \varphi_1(t) = t^{-1}\psi(t)$ for $t > t_0$ with $\int_{t_0}^\infty t^{-1}|\psi(t) - c|dt < \infty$.
Then
(i) If $p = 0$, then $\mathfrak{D}(\Phi_{\varphi_0}) = I_{\log}(\mathbb{R}^d)$.
(ii) If $0 < p < 1$, then $\mathfrak{D}(\Phi_{\varphi_p}) = \{\mu \in I(\mathbb{R}^d) : \int_{\mathbb{R}^d} |x|^p\mu(dx) < \infty\} =: I_p(\mathbb{R}^d)$.
(iii) If $p = 1$, then $\mathfrak{D}(\Phi_{\varphi_1}) = \{\mu \in I(\mathbb{R}^d) : \int_{\mathbb{R}^d} |x|\mu(dx) < \infty$
$\lim_{T\to\infty} \int_{t_0}^T t^{-1}dt \int_{|x|>t} x\nu(dx)$ exists in $\mathbb{R}^d$, $\int_{\mathbb{R}^d} x\mu(dx) = 0\} =: I_1^*(\mathbb{R}^d)$.
(iv) If $1 < p < 2$, then $\mathfrak{D}(\Phi_{\varphi_p}) = \{\mu \in I(\mathbb{R}^d) : \int_{\mathbb{R}^d} |x|^p\mu(dx) < \infty, \int_{\mathbb{R}^d} x\mu(dx) = 0\}$
$=: I_p^0(\mathbb{R}^d)$.
(v) If $p \geq 2$, then $\mathfrak{D}(\Phi_{\varphi_p}) = \{\delta_0\}$, where δ_0 is the distribution with the total mass at 0.

We apply Proposition 2.2 to our problem. First we note that when $\alpha < 2$, $G^*_{\alpha,\beta}(t)$ is locally square-integrable with respect to Lebesgue measure on $[0,\infty)$.

Theorem 2.3. (*Case* $\alpha = 0$.) $\mathfrak{D}(\Psi_{0,\beta}) = I_{\log}(\mathbb{R}^d)$.

Proof. Note that $t(= G_{\alpha,\beta}(u)) \uparrow \infty$ if and only if $u(= G^*_{\alpha,\beta}(t)) \downarrow 0$, when $\alpha \geq 0$. It is enough to show that for some $C_1 \in (0,\infty)$, $u \sim C_1 e^{-t}$ as $t \to \infty$. We have

$$\begin{aligned}
\frac{u}{e^{-t}} &= \frac{u}{\exp\{-G_{0,\beta}(u)\}} = \exp\{G_{0,\beta}(u) + \log u\} = \exp\left\{\int_u^\infty x^{-1}e^{-x^\beta}dx + \log u\right\} \\
&= \exp\left\{\beta^{-1}\int_{u^\beta}^\infty y^{-1}e^{-y}dy - \beta^{-1}\int_{u^\beta}^1 y^{-1}dy\right\} \\
&= \exp\left\{\beta^{-1}\int_{u^\beta}^1 y^{-1}(e^{-y}-1)dy + \beta^{-1}\int_1^\infty y^{-1}e^{-y}dy\right\} \to C_1,
\end{aligned}$$

say, as $u \downarrow 0$. Hence $u \sim C_1 e^{-t}$ as $t \to \infty$, and the condition (1) of Proposition 2.2 is satisfied. Thus Proposition 2.2 (i) gives us the assertion. $\square$

Theorem 2.4. (*Case* $\alpha \in (0,\infty)$.)
(i) *If* $0 < \alpha < 1$, *then* $\mathfrak{D}(\Psi_{\alpha,\beta}) = I_\alpha(\mathbb{R}^d)$.
(ii) *If* $\alpha = 1$, *then* $\mathfrak{D}(\Psi_{1,\beta}) = I_1^*(\mathbb{R}^d)$.
(iii) *If* $1 < \alpha < 2$, *then* $\mathfrak{D}(\Psi_{\alpha,\beta}) = I_\alpha^0(\mathbb{R}^d)$.
(iv) *If* $\alpha \geq 2$, *then* $\mathfrak{D}(\Psi_{\alpha,\beta}) = \{\delta_0\}$.

Proof. (i) and (iii). It is enough to show that $u \sim C_2 t^{-1/\alpha}$ as $t \to \infty$ for some $C_2 \in (0,\infty)$. We have, as $t \to \infty$ (equivalently $u \downarrow 0$), for some $C_3 \in (0,\infty)$,

$$\frac{u}{t^{-1/\alpha}} = \frac{u}{\left(G_{\alpha,\beta}(u)\right)^{-1/\alpha}} = \frac{u}{\left(\beta^{-1}\int_{u^\beta}^\infty y^{-(\alpha/\beta)-1}e^{-y}dy\right)^{-1/\alpha}} \sim \frac{u}{\left(C_3 u^{-\alpha}\right)^{-1/\alpha}} = C_3^{1/\alpha} =: C_2,$$

and the condition (2) of Proposition 2.3 is satisfied. Thus Proposition 2.3 (ii) and (iv) give us the assertions.
(ii). Suppose $\beta \neq 1$. (The case $\beta = 1$ is proved in Sato (2006b).) We first have

$$\begin{aligned}
G_{1,\beta}(u) &= \int_u^\infty x^{-2}e^{-x^\beta}dx = \int_u^\infty x^{-2}dx + \int_u^\infty x^{-2}(e^{-x^\beta}-1)dx \\
&= \int_u^\infty x^{-2}dx + \int_u^1 x^{-2}(e^{-x^\beta}-1+x^\beta)du - \int_u^1 x^{-2+\beta}dx + \int_1^\infty x^{-2}(e^{-x^\beta}-1)dx \\
&= u^{-1} + (\beta-1)^{-1}u^{-1+\beta} + O(1),\ u \downarrow 0.
\end{aligned}$$

Thus

$$t = G^*_{1,\beta}(t)^{-1} + (\beta-1)^{-1}G^*_{1,\beta}(t)^{-1+\beta} + O(1),\ t \to \infty.$$

Therefore,

$$G^*_{1,\beta}(t) = t^{-1} + (\beta-1)^{-1}t^{-1}G^*_{1,\beta}(t)^\beta + O(t^{-1}G^*_{1,\beta}(t)),\ t \to \infty. \tag{2.1}$$

We have shown in (i) and (iii) that $u \sim C_2 t^{-1/\alpha}$, but this is also true for $\alpha = 1$. Hence

$$u = G^*_{1,\beta}(t) = C_2 t^{-1}(1 + o(1)),\ t \to \infty. \tag{2.2}$$

By substituting (2.2) into (2.1), we have

$$\begin{aligned} G^*_{1,\beta}(t) &= t^{-1} + C_2^{\beta}(\beta-1)^{-1}t^{-1-\beta} + t^{-1}a(t),\ t\to\infty, \\ &= t^{-1}\left(1 + C_2^{\beta}(\beta-1)^{-1}t^{-\beta} + a(t)\right),\ t\to\infty, \end{aligned}$$

where

$$a(t) = \begin{cases} o(t^{-\beta}),\ t\to\infty, & \text{when } 0<\beta<1, \\ O(t^{-1}),\ t\to\infty, & \text{when } \beta>1. \end{cases}$$

Thus

$$G^*_{1,\beta}(t) = t^{-1}\psi(t),$$

where

$$\psi(t) := 1 + C_2^{\beta}(\beta-1)^{-1}t^{-\beta} + a(t),$$

and

$$\int_1^\infty t^{-1}|\psi(t)-1|dt = \int_1^\infty t^{-1}|C_2^{\beta}(\beta-1)^{-1}t^{-\beta} + a(t)|dt < \infty.$$

Thus the condition (3) of Proposition 2.2 is satisfied with $t_0 = 1$ and $c = 1$, and Proposition 2.2 (iii) gives us the assertion (iii).
(iv) The same as in Sato (2006b). ☐

We now calculate the Lévy measure of $\widetilde{\mu} = \Psi_{\alpha,\beta}(\mu)$, and note that the mapping $\Psi_{\alpha,\beta}$ is one-to-one.

Lemma 2.5. *Let $\alpha < 2$ and $\beta > 0$. Let $\mu \in \mathfrak{D}(\Psi_{\alpha,\beta})$ and $\widetilde{\mu} = \Psi_{\alpha,\beta}(\mu)$, and let ν and $\widetilde{\nu}$ be the Lévy measures of μ and $\widetilde{\mu}$, respectively.*
(1) *We have*

$$\widetilde{\nu}(B) = \int_0^\infty \nu(s^{-1}B)s^{-\alpha-1}e^{-s^{\beta}}ds, \quad B \in \mathscr{B}(\mathbb{R}^d\setminus\{0\}). \tag{2.3}$$

(2) *If $\nu \neq 0$, and ν has polar decomposition (λ, ν_ξ), then a polar decomposition of $\widetilde{\nu} = (\widetilde{\lambda}, \widetilde{\nu}_\xi)$ is given by $\widetilde{\lambda} = \lambda$ and $\widetilde{\nu}_\xi(dr) = r^{-\alpha-1}\widetilde{g}_\xi(r^{\beta})dr$, where*

$$\widetilde{g}_\xi(u) = \int_0^\infty r^{\alpha}e^{-u/r^{\beta}}\nu_\xi(dr). \tag{2.4}$$

(3) *$\widetilde{g}_\xi$ in (2.4) satisfies the requirements of g_ξ in (1.2).*

Proof. Suppose $\mu \in \mathfrak{D}(\Psi_{\alpha,\beta})$ and $\widetilde{\mu} = \Psi_{\alpha,\beta}(\mu)$.
(1) We see that (by using Proposition 2.6 of Sato (2006b)),

$$\begin{aligned} \widetilde{\nu}(B) &= \int_0^{G_{\alpha,\beta}(0)} dt \int_{\mathbb{R}^d} 1_B(xG^*_{\alpha,\beta}(t))\nu(dx) = -\int_0^\infty dG_{\alpha,\beta}(s)\int_{\mathbb{R}^d} 1_B(xs)\nu(dx) \\ &= \int_0^\infty s^{-\alpha-1}e^{-s^{\beta}}ds \int_{\mathbb{R}^d} 1_{s^{-1}B}(x)\nu(dx) = \int_0^\infty \nu(s^{-1}B)s^{-\alpha-1}e^{-s^{\beta}}ds, \end{aligned}$$

which is (2.3).

(2) Next assume that $\nu \neq 0$ and ν has polar decomposition (λ, ν_ξ). Then, we have

$$\begin{aligned}\widetilde{\nu}(B) &= \int_0^\infty s^{-\alpha-1} e^{-s^\beta} ds \int_S \lambda(d\xi) \int_0^\infty 1_{s^{-1}B}(r\xi)\nu_\xi(dr) \\ &= \int_S \lambda(d\xi) \int_0^\infty \nu_\xi(dr) r^{-1} \int_0^\infty (u/r)^{-\alpha-1} e^{-(u/r)^\beta} 1_B(u\xi) du \\ &= \int_S \lambda(d\xi) \int_0^\infty 1_B(u\xi) u^{-\alpha-1} \widetilde{g}_\xi(u^\beta) du,\end{aligned}$$

where $\widetilde{\lambda} = \lambda$ and

$$\widetilde{g}_\xi(u) = \int_0^\infty r^\alpha e^{-u/r^\beta} \nu_\xi(dr), \tag{2.5}$$

which is (2.4). The finiteness of $\widetilde{g}_\xi$ is trivial for $\alpha \le 0$. For $\alpha > 0$, since $\mu \in \mathfrak{D}(\Psi_{\alpha,\beta})$, we have that $\int_{\mathbb{R}^d} |x|^\alpha \mu(dx) < \infty$. When $\alpha > 0$, note that $\int_{\mathbb{R}^d} |x|^\alpha \mu(dx) < \infty$ implies $\int_1^\infty r^\alpha \nu_\xi(dr) < \infty$, (see, e.g. Sato (1999), Theorem 25.3). Hence the integral $\widetilde{g}_\xi$ exists.
(3) If we put

$$\widetilde{Q}(B) = \int_0^\infty r^\alpha 1_B(r^{-\beta}) \nu_\xi(dr),$$

then it follows that $\widetilde{g}_\xi(u) = \int_0^\infty e^{-uy} \widetilde{Q}(dy)$, and thus $\widetilde{g}_\xi$ is completely monotone by Bernstein's theorem. If $\alpha \le 0$, then automatically $\lim_{u\to\infty} \widetilde{g}_\xi(u) = 0$ λ-a.e. ξ, since

$$\infty > \int_{|x|>1} \widetilde{\nu}(dx) = \int_S \lambda(d\xi) \int_1^\infty u^{-\alpha-1} \widetilde{g}_\xi(u^\beta) du.$$

When $\alpha > 0$, since $\int_1^\infty r^\alpha \nu_\xi(dr) < \infty$, the assertion that $\lim_{u\to\infty} \widetilde{g}_\xi(u) = 0$ λ-a.e. ξ also follows from (2.5) by the dominated convergence theorem.
The proof of the lemma is thus concluded. □

Remark 2.6. *(2.3) can be written as, by introducing a transformation $\Upsilon_{\alpha,\beta}$ of Lévy measures as $\widetilde{\nu} = \Upsilon_{\alpha,\beta}(\nu)$. Then this $\Upsilon_{\alpha,\beta}$ is a generalized Upsilon transformation discussed in Barndorff-Nielsen et al. (2008) with the dilation measure $\tau(ds) = s^{-\alpha-1} e^{-s^\beta} ds$.*

Theorem 2.7. *For each $\alpha < 2$ and $\beta > 0$, the mapping $\Psi_{\alpha,\beta}$ is one-to-one.*

The proof is carried out in the same way as for Proposition 4.1 of Sato (2006b).

We are now ready to discuss stochastic integral characterizations of the classes $J_{\alpha,\beta}(\mathbb{R}^d)$, by showing that $J_{\alpha,\beta}(\mathbb{R}^d)$ is the range of the mapping $\Psi_{\alpha,\beta}$. However, in this paper, we restrict ourselves to the case $\alpha < 1$, because in the case $1 \le \alpha < 2$, $J_{\alpha,\beta}(\mathbb{R}^d)$ is strictly bigger than the range $\Psi_{\alpha,\beta}(\mathfrak{D}(\Psi_{\alpha,\beta}))$ and more deep calculations would be needed. (See, e.g., Sato (2006b) and Maejima et al. (2009).) Also, the classes appearing in our motivation of introducing the classes $J_{\alpha,\beta}(\mathbb{R}^d)$ are restricted to the case $\alpha \le 0$.

Theorem 2.8. *Let $\alpha < 1$ and $\beta > 0$. The range of the mapping $\Psi_{\alpha,\beta}$ equals $J_{\alpha,\beta}(\mathbb{R}^d)$, that is,*

$$J_{\alpha,\beta}(\mathbb{R}^d) = \Psi_{\alpha,\beta}(\mathfrak{D}(\Psi_{\alpha,\beta})).$$

Remark 2.9. *This theorem is already known for $\alpha = -1, 0$ and $\beta = 1$ in Theorems A and C of Barndorff-Nielsen et al. (2006) and for $\alpha < 1$ and $\beta = 1$ in Theorem 4.2 of Sato (2006b).*

Proof of Theorem 2.8. We first show that $\Psi_{\alpha,\beta}(\mathfrak{D}(\Psi_{\alpha,\beta})) \subset J_{\alpha,\beta}(\mathbb{R}^d)$. Suppose $\mu \in \mathfrak{D}(\Psi_{\alpha,\beta})$ and $\widetilde{\mu} = \Psi_{\alpha,\beta}(\mu)$, and let ν and $\widetilde{\nu}$ be the Lévy measures of μ and $\widetilde{\mu}$, respectively. Thus, if $\nu = 0$, then $\widetilde{\nu} = 0$ and $\widetilde{\mu} \in J_{\alpha,\beta}(\mathbb{R}^d)$. When $\nu \neq 0$, it follows from Lemma 2.5 that $\widetilde{\mu} \in J_{\alpha,\beta}(\mathbb{R}^d)$.
Next we show that $J_{\alpha,\beta}(\mathbb{R}^d) \subset \Psi_{\alpha,\beta}(\mathfrak{D}(\Psi_{\alpha,\beta}))$. Suppose $\widetilde{\mu} \in J_{\alpha,\beta}(\mathbb{R}^d)$ with the Lévy-Khintchine triplet $(\widetilde{A}, \widetilde{\nu}, \widetilde{\gamma})$. If $\widetilde{\nu} = 0$, then $\widetilde{\mu} = \Psi_{\alpha,\beta}(\mu)$ for some $\mu \in \mathfrak{D}(\Psi_{\alpha,\beta})$. Thus, suppose that $\widetilde{\nu} \neq 0$. Then, in a polar decomposition $(\widetilde{\lambda}, \widetilde{\nu}_\xi)$ of $\widetilde{\nu}$, we have $\widetilde{\nu}_\xi(dr) = r^{-\alpha-1}\widetilde{g}_\xi(r^\beta)dr$, where $\widetilde{g}_\xi(v)$ is completely monotone in $v > 0$ $\widetilde{\lambda}$-a.e. ξ, and is measurable in ξ. Thus by Bernstein's theorem, there are measures $\widetilde{Q}_\xi$ on $[0,\infty)$ such that

$$\widetilde{g}_\xi(v) = \int_{[0,\infty)} e^{-vu}\widetilde{Q}_\xi(du).$$

In general, $\widetilde{Q}_\xi$ is a measure on $[0,\infty)$, but since $\lim_{v\to\infty} \widetilde{g}_\xi(v) = 0$ $\widetilde{\lambda}$-a.e. ξ, $\widetilde{Q}_\xi$ does not have a point mass at 0, and hence $\widetilde{Q}_\xi$ is a measure on $(0,\infty)$. We see that

$$\begin{aligned}\widetilde{\nu}(B) &= \int_S \widetilde{\lambda}(d\xi)\int_0^\infty 1_B(r\xi)r^{-\alpha-1}\widetilde{g}_\xi(r^\beta)dr \\ &= \int_S \widetilde{\lambda}(d\xi)\int_0^\infty 1_B(r\xi)r^{-\alpha-1}dr\int_0^\infty e^{-r^\beta u}\widetilde{Q}_\xi(du).\end{aligned} \tag{2.6}$$

Since $\int_{\mathbb{R}^d}(|x|^2 \wedge 1)\widetilde{\nu}(dx) < \infty$, we have

$$\int_S \widetilde{\lambda}(d\xi)\int_0^1 r^{1-\alpha}dr\int_1^\infty e^{-r^\beta u}\widetilde{Q}_\xi(du) + \int_S \widetilde{\lambda}(d\xi)\int_1^\infty r^{-\alpha-1}dr\int_0^1 e^{-r^\beta u}\widetilde{Q}_\xi(du) < \infty.$$

Hence, we have, by the change of variables $r \to v$ by $r^\beta u = v$,

$$\begin{aligned}&\int_0^1 r^{1-\alpha}dr\int_1^\infty e^{-r^\beta u}\widetilde{Q}_\xi(du) = \int_1^\infty \widetilde{Q}_\xi(du)\int_0^1 r^{1-\alpha}e^{-r^\beta u}dr \\ &\quad = \beta^{-1}\int_1^\infty u^{(\alpha-2)/\beta}\widetilde{Q}_\xi(du)\int_0^u v^{-1+(2-\alpha)/\beta}e^{-v}dv \ge C_4\int_1^\infty u^{(\alpha-2)/\beta}\widetilde{Q}_\xi(du),\end{aligned}$$

where

$$C_4 = \beta^{-1}\int_0^1 v^{-1+(2-\alpha)/\beta}e^{-v}dv \in (0,\infty).$$

Thus

$$\int_S \widetilde{\lambda}(d\xi)\int_1^\infty u^{(\alpha-2)/\beta}\widetilde{Q}_\xi(du) < \infty. \tag{2.7}$$

We also have for any $\alpha < 1$,

$$\int_1^\infty r^{-\alpha-1}dr\int_0^1 e^{-r^\beta u}\widetilde{Q}_\xi(du) = \int_0^1 \widetilde{Q}_\xi(du)\int_1^\infty r^{-\alpha-1}e^{-r^\beta u}dr \tag{2.8}$$

$$= \beta^{-1}\int_0^1 u^{\alpha/\beta}\widetilde{Q}_\xi(du)\int_u^\infty v^{-1-(\alpha/\beta)}e^{-v}dv \ge C_5\int_0^1 u^{\alpha/\beta}\widetilde{Q}_\xi(du),$$

where

$$C_5 = \beta^{-1}\int_1^\infty v^{-1-(\alpha/\beta)}e^{-v}dv \in (0,\infty).$$

Thus

$$\int_S \widetilde{\lambda}(d\xi)\int_0^1 u^{\alpha/\beta}\widetilde{Q}_\xi(du) < \infty. \tag{2.9}$$

In addition, if $\alpha = 0$, (2.8) is turned out to be

$$\begin{aligned}\int_1^\infty r^{-1}dr\int_0^1 e^{-r^\beta u}\widetilde{Q}_\xi(du) &= \beta^{-1}\int_0^1 \widetilde{Q}_\xi(du)\int_u^1 v^{-1}e^{-v}dv\\ &\ge (\beta e)^{-1}\int_0^1 \widetilde{Q}_\xi(du)\int_u^1 v^{-1}dv = (\beta e)^{-1}\int_0^1(-\log u)\widetilde{Q}_\xi(du).\end{aligned}$$

Thus, when $\alpha = 0$,

$$\int_S \widetilde{\lambda}(d\xi)\int_0^1(-\log u)\widetilde{Q}_\xi(du) < \infty. \tag{2.10}$$

Furthermore,

$$\int_1^\infty r^{-\alpha-1}dr\int_0^1 e^{-r^\beta u}\widetilde{Q}(du) \ge \int_1^\infty r^{-\alpha-1}e^{-r^\beta}dr\int_0^1 \widetilde{Q}_\xi(du) = C_6\int_0^1 \widetilde{Q}_\xi(du),$$

where

$$C_6 := \int_1^\infty r^{-\alpha-1}e^{-r^\beta}dr \in (0,\infty).$$

Thus we have

$$\int_S \widetilde{\lambda}(d\xi)\int_0^1 \widetilde{Q}_\xi(dr) < \infty. \tag{2.11}$$

Define

$$\nu_\xi(B) = \int_0^\infty u^{\alpha/\beta}1_B\left(u^{-1/\beta}\right)\widetilde{Q}_\xi(du), \quad B \in \mathscr{B}((0,\infty)). \tag{2.12}$$

Then, it follows from (2.7) and (2.9) that

$$\begin{aligned}\int_S \widetilde{\lambda}(d\xi)\int_0^\infty (r^2\wedge 1)\nu_\xi(dr) &= \int_S \widetilde{\lambda}(d\xi)\int_0^\infty u^{\alpha/\beta}(u^{-2/\beta}\wedge 1)\widetilde{Q}_\xi(du) \\ &= \int_S \widetilde{\lambda}(d\xi)\left(\int_0^1 u^{\alpha/\beta}\widetilde{Q}_\xi(du) + \int_1^\infty u^{(\alpha-2)/\beta}\widetilde{Q}_\xi(du)\right) < \infty.\end{aligned} \tag{2.13}$$

Define ν by

$$\nu(B) = \int_S \widetilde{\lambda}(d\xi)\int_0^\infty 1_B(r\xi)\nu_\xi(dr). \tag{2.14}$$

Then, by (2.13), ν is the Lévy measure of some infinitely divisible distribution μ, and μ belongs to $\mathfrak{D}(\Psi_{\alpha,\beta})$ and satisfies

$$\widetilde{\nu}(B)=\int_0^{G_{\alpha,\beta}(0)}\nu((G^*_{\alpha,\beta}(t))^{-1}B)dt. \tag{2.15}$$

To show (2.15), by (2.6), (2.12) and (2.14), we have

$$\begin{aligned}
\widetilde{\nu}(B)&=\int_S\widetilde{\lambda}(d\xi)\int_0^\infty 1_B(r\xi)r^{-\alpha-1}dr\int_0^\infty e^{-r^\beta u}\widetilde{Q}_\xi(du)\\
&=\int_S\widetilde{\lambda}(d\xi)\int_0^\infty 1_B(u^{-1/\beta}s\xi)s^{-\alpha-1}e^{-s^\beta}ds\int_0^\infty u^{\alpha/\beta}\widetilde{Q}_\xi(du)\\
&=\int_0^\infty s^{-\alpha-1}e^{-s^\beta}ds\int_S\widetilde{\lambda}(d\xi)\int_0^\infty 1_B(u^{-1/\beta}s\xi)u^{\alpha/\beta}\widetilde{Q}_\xi(du)\\
&=\int_0^\infty s^{-\alpha-1}e^{-s^\beta}ds\int_S\widetilde{\lambda}(d\xi)\int_0^\infty 1_B(rs\xi)\nu_\xi(dr)\\
&=\int_0^\infty s^{-\alpha-1}e^{-s^\beta}ds\int_S\widetilde{\lambda}(d\xi)\int_0^\infty 1_{s^{-1}B}(r\xi)\nu_\xi(dr)\\
&=\int_0^\infty \nu(s^{-1}B)s^{-\alpha-1}e^{-s^\beta}ds=-\int_0^\infty\nu(s^{-1}B)dG_{\alpha,\beta}(s)\\
&=\int_0^{G_{\alpha,\beta}(0)}\nu((G^*_{\alpha,\beta}(t))^{-1}B)dt.
\end{aligned}$$

To show that $\mu\in\mathfrak{D}(\Psi_{\alpha,\beta})$, it is enough to show that $\int_{|x|>1}|x|^\alpha\nu(dx)<\infty$, which is if and only if $\mu\in I_\alpha(\mathbb{R}^d)$, when $0<\alpha<1$, and $\int_{|x|>1}\log|x|\nu(dx)<\infty$, which is if and only if $\mu\in I_{\log}(\mathbb{R}^d)$, when $\alpha=0$, (see Sato (1999), Theorem 25.3). Note that by (2.12) we see, for any nonnegative measurable function f on $(0,\infty)$,

$$\int_0^\infty f(r)\nu_\xi(dr)=\int_0^\infty u^{\alpha/\beta}f(u^{-1/\beta})\widetilde{Q}_\xi(du).$$

Thus if we choose $f(r)=I[r>1]r^\alpha$, where $I[A]$ is the indicator function of the set A, then ν in (2.14) satisfies that for $\alpha>0$

$$\int_{|x|>1}|x|^\alpha\nu(dx)=\int_S\widetilde{\lambda}(d\xi)\int_1^\infty r^\alpha\nu_\xi(dr)=\int_S\widetilde{\lambda}(d\xi)\int_0^1\widetilde{Q}_\xi(du)<\infty \tag{2.16}$$

due to (2.11). When $\alpha=0$,

$$\begin{aligned}
&\int_{|x|>1}\log|x|\nu(dx)=\int_S\widetilde{\lambda}(d\xi)\int_1^\infty\log r\nu_\xi(dr) \qquad (2.17)\\
&=\int_S\widetilde{\lambda}(d\xi)\int_0^1\log u^{-1/\beta}\widetilde{Q}_\xi(du)=\beta^{-1}\int_S\widetilde{\lambda}(d\xi)\int_0^1(-\log u)\widetilde{Q}_\xi(du)<\infty
\end{aligned}$$

due to (2.10).

Notice again that

$$\int_0^{G_{\alpha,\beta}(0)} \left(G^*_{\alpha,\beta}(t)\right)^2 dt = -\int_0^\infty u^2 dG_{\alpha,\beta}(u) = \int_0^\infty u^{1-\alpha} e^{-u^\beta} du < \infty.$$

Define A and γ by

$$\widetilde{A} = \left(\int_0^{G_{\alpha,\beta}(0)} G^*_{\alpha,\beta}(t)^2 dt\right) A \tag{2.18}$$

and

$$\widetilde{\gamma} = \int_0^{G_{\alpha,\beta}(0)} G^*_{\alpha,\beta}(t)dt \left(\gamma + \int_{\mathbb{R}^d} x\left(\frac{1}{1+|G^*_{\alpha,\beta}(t)x|^2} - \frac{1}{1+|x|^2}\right)\nu(dx)\right). \tag{2.19}$$

Here we have to check the finiteness of this integral. We first have

$$\int_0^{G_{\alpha,\beta}(0)} G^*_{\alpha,\beta}(t)dt = -\int_0^\infty u dG_{\alpha.\beta}(u) = \int_0^\infty u^{-\alpha} e^{-u^\beta} du < \infty,$$

since $\alpha < 1$. Below, $C_7, C_8 \in (0,\infty)$ are suitable constants. Recall $\alpha < 1$. When $\alpha \neq 0$, we have

$$\begin{aligned}
&\int_0^{G_{\alpha,\beta}(0)} G^*_{\alpha,\beta}(t)dt \int_{\mathbb{R}^d} |x| \left|\frac{1}{1+|G^*_{\alpha,\beta}(t)x|^2} - \frac{1}{1+|x|^2}\right| \nu(dx)\\
&= \int_0^\infty u^{-\alpha} e^{-u^\beta} du \int_{\mathbb{R}^d} |x| \left|\frac{1}{1+|ux|^2} - \frac{1}{1+|x|^2}\right| \nu(dx)\\
&\le \int_0^\infty u^{-\alpha}(1+u^2) e^{-u^\beta} du \int_{\mathbb{R}^d} \frac{|x|^3}{(1+|ux|^2)(1+|x|^2)} \nu(dx)\\
&\le \int_0^\infty u^{-\alpha}(1+u^2) e^{-u^\beta} du\\
&\qquad \times \left(\int_{|x|\le 1} |x|^2 \nu(dx) + \int_{|x|>1, |ux|\le 1} |x|\nu(dx) + \int_{|x|>1,|ux|>1} \frac{|x|}{|ux|^2}\nu(dx)\right)\\
&= C_7 + \int_{|x|>1} |x|\nu(dx) \int_0^{1/|x|} u^{-\alpha}(1+u^2) e^{-u^\beta} du\\
&\qquad + \int_{|x|>1} \nu(dx) \int_{1/|x|}^\infty u^{-\alpha-1}(1+u^2) e^{-u^\beta} du\\
&\le C_7 + \int_{|x|>1} |x|\nu(dx) \int_0^{1/|x|} 2u^{-\alpha} du\\
&\qquad + \int_{|x|>1} \nu(dx) \left\{\left(\int_{1/|x|}^1 + \int_1^\infty\right) u^{-\alpha-1}(1+u^2) e^{-u^\beta} du\right\}\\
&\le C_7 + 2(1-\alpha)^{-1} \int_{|x|>1} |x|^\alpha \nu(dx)\\
&\qquad + \int_{|x|>1} \nu(dx) \left\{\int_{1/|x|}^1 2u^{-\alpha-1} du + \int_1^\infty u^{-\alpha-1}(1+u^2) e^{-u^\beta} du\right\}
\end{aligned} \tag{2.20}$$

$$
\begin{aligned}
&= C_7 + 2(1-\alpha)^{-1} \int_{|x|>1} |x|^\alpha \nu(dx) \\
&\qquad + \int_{|x|>1} \nu(dx) \left\{ -2\alpha^{-1}(1-|x|^\alpha) + C_8 \right\} \\
&= C_7 + 2(1-\alpha)^{-1} \int_{|x|>1} |x|^\alpha \nu(dx) \\
&\qquad + 2\alpha^{-1} \int_{|x|>1} |x|^\alpha \nu(dx) + (C_8 - 2\alpha^{-1}) \int_{|x|>1} \nu(dx) < \infty,
\end{aligned} \tag{2.21}
$$

by (2.16). When $\alpha = 0$, since

$$
\int_{1/|x|}^{1} u^{-\alpha-1} du = \int_{1/|x|}^{1} u^{-1} du = \log |x|,
$$

in (2.20), we have

$$
\int_{|x|>1} \log |x| \nu(dx) \tag{2.22}
$$

instead of $\int_{|x|>1} |x|^\alpha \nu(dx)$ in (2.21) in the calculation above. The finiteness of (2.22) is assured by (2.17).

Thus γ can be defined. Hence, if we denote by μ an infinitely divisible distribution having the Lévy-Khintchine triplet (A, ν, γ) above, then by (2.15), (2.18) and (2.19), we see that

$$
\widetilde{\mu} = \mathscr{L}\left(\int_0^{G_{\alpha,\beta}(0)} G^*_{\alpha,\beta}(t) dX_t^{(\mu)} \right),
$$

concluding that $\widetilde{\mu} \in \Psi_{\alpha,\beta}(\mathfrak{D}(\Psi_{\alpha,\beta}))$. This completes the proof. $\square$

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