

Markov processes and generalized Schrödinger equations

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Abstract

Starting from the forward and backward infinitesimal generators of bilateral, time-homogeneous Markov processes, the self-adjoint Hamiltonians of the generalized Schrödinger equations are first introduced by means of suitable Doob transformations. Then, by broadening with the aid of the Dirichlet forms the results of the Nelson stochastic mechanics, we prove that it is possible to associate bilateral, and time-homogeneous Markov processes to the wave functions stationary solutions of our generalized Schrödinger equations. Particular attention is then paid to the special case of the Lévy-Schrödinger (L - S) equations and to their associated Lévy-type Markov processes, and to a few examples of Cauchy background noise.

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1 Introduction

In a few recent papers [1] it has been proposed to broaden the scope of the well known relation between the Wiener process and the Schrödinger equation [2, 3, 4, 5]

to other suitable Markov processes. This idea – already introduced elsewhere, but essentially only for stable processes [6, 7] – led to a L - S (Lévy–Schrödinger) equation containing additional integral terms which take into account the possible jumping part of the background noise. This equation has been presented in the framework of *stochastic mechanics* [2, 5] as a model for systems more general than just the usual quantum mechanics: namely as a true *dynamical theory of Lévy processes* that can find applications in several physical fields [8]. However in the previous papers [1] our discussion was essentially heuristic and rather oriented to discuss the basic ideas, and to show a number of explicit examples of wave packets solutions of these L - S equations in the free case, by pointing out the new features as for instance their time dependent *multi-modality*. The aim of the present paper is instead to pursue this enquiry by giving a rigorous presentation of the relations between the L - S equations and their background Markov processes.

In the original Nelson papers [2] the Schrödinger equation of quantum mechanics was associated to the diffusion processes weak solutions of the SDE (Stochastic Differential Equations)

$$dX_t = b(X_t, t)dt + dW_t \quad (1)$$

where W_t is a Wiener process. Our aim is then to analyze how this Nelson approach can be generalized when a wider class of Markov processes is considered instead of the diffusion processes (1), and what kind of equations are involved, in particular, when Lévy processes are considered instead of W_t . The Lévy processes [9, 10, 11, 12] can indeed be considered as the most natural generalization of the Wiener process: they have stationary, independent increments, and they are stochastically continuous. The Wiener process itself is a Lévy process, but it essentially differs from the others because it is the unique with *a.s.* (almost surely) continuous paths: the other Lévy processes, indeed, typically show random jumps all along their trajectories. In the recent years we have witnessed a considerable growth of interest in non Gaussian stochastic processes – and in particular into Lévy processes – in domains ranging from statistical mechanics to mathematical finance. In the physical field the research scope is presently focused mainly on the stable processes and on the corresponding fractional calculus [6, 7, 13], but in the financial domain a vastly more general type of processes is at present in use [14], while interesting generalizations seem to be at hand [15]. Here we suggest that the stochastic mechanics should be considered as a dynamical theory of the entire gamut of the *infinitely divisible* (not only stable) Lévy processes with time reversal invariance, and that the horizon of its applications should be widened even to cases different from the quantum systems.

This approach presents several advantages: on the one hand the use of general infinitely divisible processes lends the possibility of having realistic, *finite variances*, a situation ruled out for non Gaussian, stable processes; and on the other there are examples of non stable Lévy processes which are connected with the simplest form of the quantum, *relativistic Schrödinger equation*: a link with important physical applications that was missing in the original Nelson model and was recognized only several years later [16]. This final remark, on the other hand, shows that the

present inquiry is not only justified by the a desire of formal generalization, but is required by the need to attain physically meaningful cases that otherwise would not be contemplated in the narrower precinct of the stable laws.

To give a rigorous justification of the L-S equation, essentially introduced in [1] by means of an analogy, let us first remark that the original Nelson approach for deriving the Schrödinger equation was based on a deep understanding of the *dynamics* of the stochastic processes, while this reckoned on new definitions of the kinematical quantities – *forward and backward mean velocities* and *mean accelerations* – that anyway safely revert to the ordinary ones when the processes degenerate in deterministic trajectories. For the time being, however, our approach will be rather different: we will not resort openly to an underlying dynamics, but starting instead with the infinitesimal generators L of a semigroup in a Hilbert space we will explore on the one hand under what conditions we can associate it to a suitable Markov process $X_t \in \mathbf{R}^n$ with *pdf* (probability density function) ρ_t ; and on the other the formal procedures leading from L to a self-adjoint, bounded from below operator H on $\mathcal{L}_C^2(\mathbf{R}^n, d^n x)$ and to a wave function $\Psi_t \in \mathcal{L}_C^2(\mathbf{R}^n, d^n x)$ which turns out to be a solution of the *generalized Schrödinger equation*

$$i\partial_t \Psi_t = H\Psi_t \quad (2)$$

with $|\Psi_t|^2 = \rho_t$, $\forall t \in \mathbf{R}$. While the first task will be accomplished by resorting to the properties of the Dirichlet forms \mathcal{E} [17, 18] that can be defined from L , the second result will be obtained by following the path of the Doob transformations [19, 20].

The paper is then organized as follows: while in the Section 2 we will first recall the less usual features of the Markov processes of our interest, in the Section 3 we will introduce their associated infinitesimal generators and Dirichlet forms, and in the subsequent Section 4 we will briefly summarize the essential notations about the Lévy processes. In the Section 6 we will then recall how, by means of the Doob transformations previously defined in the Section 5, the stationary solutions of the usual Schrödinger equation actually admit a stochastic representation in terms of the diffusion processes (1). Finally in the Section 7 we will focus our attention on our main result about the Lévy-type [21], Markov processes associated to the stationary solutions of the *L-S (Lévy-Schrödinger)* equation

$$i\partial_t \Psi_t = -L_0 \Psi_t + V\Psi_t \quad (3)$$

which is a particular form of (2). Here V is a suitable real function, while for an infinitely derivable function on \mathbf{R}^n with compact support $f \in C_0^\infty(\mathbf{R}^n)$, L_0 explicitly operates in the following way

$$[L_0 f](x) = \alpha_{ij} \partial_{ij}^2 f(x) + \int_{y \neq 0} [f(x+y) - f(x) - \mathbf{1}_{B_1}(y) y_i \partial_i f(x)] \ell(dy)$$

where α_{ij} is a symmetric, positive definite matrix, $\mathbf{1}_{B_1}(y)$ is the indicator of the set $B_1 = \{y \in \mathbf{R}^n : |y| \leq 1\}$, and $\ell(dy)$ is a *Lévy measure* [9, 10]. The name of the

equation (3) is due to the fact that L_0 turns out to be the infinitesimal generator of a symmetric Lévy process, while V plays the role of a potential, so that (3) closely resembles the usual Schrödinger equation that one obtains when L_0 is the infinitesimal generator of a Wiener process. In the last Section 8 a few examples of stationary states of Cauchy-Schrödinger equations with their associated Lévy-type processes are explicitly discussed.

2 Markov Processes

A stochastic processes X_t is usually defined for $t \geq 0$, but it will be important for us to consider also processes defined for every $t \in \mathbf{R}$: we will call them *bilateral processes*. This will allow us to introduce *forward* and *backward* representations that will be instrumental to define the suitable symmetric operators and the self-adjoint Hamiltonians needed in our generalized Schrödinger equations. It will be useful, moreover, to recall that we will call a process X_t *stationary* when all its joint distributions (for a Markov process, those at one and two times are enough) are invariant for a change of the time origin. In this case the distributions at one time are invariants, and the conditional (transition) distributions depend only on the time differences. On the other hand we will call it *time-homogeneous* when just the conditional (transition) distributions are independent from the time origin and depend only on the time differences. In this case however the process can possibly be non stationary when the one-time distributions are not constant, and as a consequence the joint distributions depend on the changes of the time origin.

Let then $X = (X_t)_{t \in \mathbf{R}}$ be a bilateral, time-homogeneous Markov process defined on a probability space $(\Omega, \mathcal{F}, \mathbb{P})$ endowed with its natural filtration, and taking values on $(\mathbf{R}^n, \mathcal{B}(\mathbf{R}^n))$. We will first of all denote respectively by p_t and \tilde{p}_t its *forward and backward transition functions* defined as

$$p_t(x, B) := \mathbb{P}\{X_{s+t} \in B \mid X_s = x\}, \quad \tilde{p}_t(x, B) := \mathbb{P}\{X_{s-t} \in B \mid X_s = x\} \quad (4)$$

for $s \in \mathbf{R}$, $t \geq 0$, $x \in \mathbf{R}^n$ and $B \in \mathcal{B}(\mathbf{R}^n)$. We will say that μ is an invariant measure for X when

$$\mu(B) = \int p_t(x, B) \mu(dx) = \int \tilde{p}_t(x, B) \mu(dx) \quad t > 0$$

for $B \in \mathcal{B}(\mathbf{R}^n)$. Remark that here μ is not necessarily supposed to be a *probability* measure. As a consequence X can be an *improper process*, namely a process which is properly defined as a measurable application from an underlying probabilizable space into a trajectory space and is adapted to a filtration, but which is endowed with a measure which is not finite. In particular we will find instrumental the use of the Lebesgue measure that turns out to be invariant for many of our semigroups and can consequently be adopted as the overall measure of the process. This is on the other hand not new if we think to the case of plane waves solutions of the Schrödinger equation in quantum mechanics.

Given an invariant measure μ it is possible to prove [22] that, always for $t \geq 0$, we can define on $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ endowed with the usual scalar product $\langle f, g \rangle_\mu$ the two semigroups

$$\begin{aligned} [T_t f](x) &:= \int f(y) p_t(x, dy) = \mathbb{E}\{f(X_{s+t}) \mid X_s = x\} \\ [\tilde{T}_t f](x) &:= \int f(y) \tilde{p}_t(x, dy) = \mathbb{E}\{f(X_{s-t}) \mid X_s = x\} = \mathbb{E}\{f(X_s) \mid X_{s+t} = x\} \end{aligned}$$

respectively called *forward and backward semigroups*. We also denote by $(L, D(L))$ and $(\tilde{L}, D(\tilde{L}))$, with the specification of their domains of definition, the corresponding infinitesimal generators. For these semigroups we now have

$$T_t^\dagger = \tilde{T}_t \quad t \geq 0 \quad (5)$$

as it is more easily seen when μ is the invariant *probability* measure of a *stationary* process X , namely when $\mu = \mathbb{P}_{X_t}$ for every $t \in \mathbf{R}$. In fact in this case we get for $f, g \in \mathcal{L}^2(\mathbf{R}^n, d\mu)$ and $t \geq 0$

$$\begin{aligned} \langle g, T_t f \rangle_\mu &= \int g [T_t f] d\mu = \int g(x) \mathbb{E}\{f(X_{s+t}) \mid X_s = x\} \mu(dx) \\ &= \mathbb{E}\{g(X_s) \mathbb{E}\{f(X_{s+t}) \mid X_s\}\} = \mathbb{E}\{g(X_s) f(X_{s+t})\} \\ &= \mathbb{E}\{f(X_{s+t}) \mathbb{E}\{g(X_s) \mid X_{s+t}\}\} = \int f(x) \mathbb{E}\{g(X_s) \mid X_{s+t} = x\} \mu(dx) \\ &= \int [\tilde{T}_t g] f d\mu = \langle \tilde{T}_t g, f \rangle_\mu \end{aligned}$$

In particular when T_t is self-adjoint so that $T_t^\dagger = \tilde{T}_t = T_t$ the Markov process X_t is also called μ -*symmetric*, while we will say that the process is simply *symmetric* when $\mathbb{P}_{X_t}(B) = \mathbb{P}_{X_t}(-B)$ for every $B \in \mathcal{B}(\mathbf{R}^n)$: these two notions are however strictly related [10]. We will moreover call the process *rotationally invariant* if $P_{X_t}(B) = P_{Z_t}(\mathbb{O}B)$ for every Borel set B and for every given orthogonal matrix \mathbb{O} .

We finally introduce also the *space-time version* [23] Y of X , namely the process

$$Y_t = (X_t, \tau_t) \quad (6)$$

on $(\mathbf{R}^{n+1}, \mathcal{B}(\mathbf{R}^{n+1}))$, with just one more *degenerate* component: $\tau_t = t$ *a.s.* It is easy to prove then that the Y forward and backward semigroups and generators – now denoted by $T_t^Y, \tilde{T}_t^Y, L^Y$ and \tilde{L}^Y – are defined on the space $\mathcal{L}^2(\mathbf{R}^{n+1}, d\mu dt)$ and verify relations similar to (5), namely $(T_t^Y)^\dagger = \tilde{T}_t^Y$. This space-time version Y will be useful for two reasons: first Y is always time-homogeneous [22], even when X it is not; second the Doob transforms of combinations of their generators (see the subsequent Section 5) will give rise exactly to the space-time operators needed to recover our generalized Schrödinger equations.

3 Dirichlet forms

Up to now we have defined semigroups starting from suitable, given Markov processes, but in this paper we will be mainly concerned with the reverse question: under which conditions can we define a Markov process from a given semigroup $(T_t)_{t \geq 0}$ on a real Hilbert space \mathfrak{H} with scalar product $\langle \cdot, \cdot \rangle$ and norm $\| \cdot \|$? This well known problem can be faced in several ways, and we will choose to approach it from the standpoint of the Dirichlet forms. We refer the reader to classical monographs [17, 18] for an extensive discussion about this argument. Let $(\mathcal{E}, D(\mathcal{E}))$ be a bilinear form on a vector sub-space $D(\mathcal{E})$ of \mathfrak{H} :

Definition 3.1. *A bilinear form is positive definite if $\mathcal{E}(u, u) \geq 0$ for $u \in D(\mathcal{E})$.*

Since positive definite, bilinear forms induce only semi-norms, we first introduce on the same $D(\mathcal{E})$ the new bilinear form

$$\mathcal{E}_1(u, v) := \mathcal{E}(u, v) + \langle u, v \rangle$$

and then we define on $D(\mathcal{E})$ the norm

$$\|u\|_1 := \sqrt{\mathcal{E}_1(u, u)}$$

Definition 3.2. *A bilinear form $(\mathcal{E}, D(\mathcal{E}))$ is said closed if $(D(\mathcal{E}), \|\cdot\|_1)$ is complete; it is said closable if for every sequence $(u_n)_{n \in \mathbf{N}}$ of elements of $D(\mathcal{E})$ converging to 0 in norm $\|\cdot\|$ and such that*

$$\lim_{n, m} \mathcal{E}(u_n - u_m, u_n - u_m) = 0$$

we have

$$\lim_n \mathcal{E}(u_n, u_n) = 0.$$

Bilinear forms can naturally be associated to linear operators L in the Hilbert space \mathfrak{H} , for instance as $\mathcal{E}(u, v) = -\langle Lu, v \rangle$. Under appropriate conditions, when L is the generator of the semigroup T_t , this would produce the required link between Markov processes and bilinear forms.

Proposition 3.3. *Let $(L, D(L))$ be a symmetric, negative definite linear operator on \mathfrak{H} , and define the bilinear form $\mathcal{E}(u, v) := -\langle Lu, v \rangle$ with $D(\mathcal{E}) := D(L)$. Then $(\mathcal{E}, D(\mathcal{E}))$ is closable.*

PROOF. See [18]

□

Definition 3.4. *Let $(\mathcal{E}, D(\mathcal{E}))$ be a closed, positive definite, bilinear form on \mathfrak{H} with $D(\mathcal{E})$ dense in \mathfrak{H} : \mathcal{E} is said to be a coercive, closed form if*

1. its symmetric part

$$\mathcal{E}_s(u, v) = \frac{\mathcal{E}(u, v) + \mathcal{E}(v, u)}{2} \quad (7)$$

is closed on $D(\mathcal{E})$

2. $(\mathcal{E}, D(\mathcal{E}))$ verify the weak sector condition, namely $\exists k > 0$ (called continuity constant) such that

$$|\mathcal{E}_1(u, v)| \leq k \|u\|_1 \cdot \|v\|_1 \quad (8)$$

for every $u, v \in D(\mathcal{E})$.

We also recall [18] here that if $(\mathcal{E}, D(\mathcal{E}))$ is a closable form on a Hilbert space \mathfrak{H} satisfying the weak sector condition (8), then it can be extended to a closed form $(\bar{\mathcal{E}}, D(\bar{\mathcal{E}}))$ called its *closure*, where $D(\bar{\mathcal{E}})$ is the set of the $u \in \mathfrak{H}$ such that

- it exists a $(u_n)_{n \in \mathbf{N}}$ of elements of $D(\mathcal{E})$ such that $u_n \rightarrow u$ in \mathfrak{H}
- $(\|u_n\|_1)_{n \in \mathbf{N}}$ is a Cauchy sequence in \mathbf{R} ,

while the form itself is defined as

$$\bar{\mathcal{E}}(u, v) := \lim_n \mathcal{E}_1(u_n, v_n) - \langle u, v \rangle \quad u, v \in D(\bar{\mathcal{E}})$$

Theorem 3.5. *Let $(\mathcal{E}, D(\mathcal{E}))$ be a coercive, closed form on \mathfrak{H} : then there exist a pair of operators $(L, D(L))$ and $(\tilde{L}, D(\tilde{L}))$ on \mathfrak{H} , with*

$$\begin{aligned} D(L) &:= \{u \in D(\mathcal{E}) \mid v \rightarrow \mathcal{E}(u, v) \text{ is continuous w.r.t. } \|\cdot\|_1 \text{ on } D(\mathcal{E})\} \\ D(\tilde{L}) &:= \{v \in D(\mathcal{E}) \mid u \rightarrow \mathcal{E}(u, v) \text{ is continuous w.r.t. } \|\cdot\|_1 \text{ on } D(\mathcal{E})\} \end{aligned}$$

and

$$\mathcal{E}(u, v) = -\langle Lu, v \rangle, \quad u \in D(L), v \in D(\mathcal{E}) \quad (9)$$

$$\mathcal{E}(u, v) = -\langle u, \tilde{L}v \rangle, \quad u \in D(\mathcal{E}), v \in D(\tilde{L}) \quad (10)$$

which are the infinitesimal generators of two strongly continuous, contraction semi-groups $(T_t)_{t \geq 0}$ and $(\tilde{T}_t)_{t \geq 0}$ such that

$$T_t^\dagger = \tilde{T}_t \quad \forall t \geq 0$$

PROOF. See [18], pag. 18. □

The subsequent exposition could well be proposed for more general Hilbert spaces, but to settle our notation from now on we will rather limit ourselves just to $\mathfrak{H} = \mathcal{L}^2(\mathbf{R}^n, d\mu)$.

Definition 3.6. A coercive, closed form $(\mathcal{E}, D(\mathcal{E}))$ on $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ is a Dirichlet form if $\forall f \in D(\mathcal{E})$ we have $f^+ \wedge 1 \in D(\mathcal{E})$ and

$$\mathcal{E}(f + f^+ \wedge 1, f - f^+ \wedge 1) \geq 0, \quad \mathcal{E}(f - f^+ \wedge 1, f + f^+ \wedge 1) \geq 0. \quad (11)$$

with $a \wedge b = \min\{a, b\}$. If only one of the above conditions is verified, then $(\mathcal{E}, D(\mathcal{E}))$ is sometimes called $\frac{1}{2}$ -Dirichlet form.

According to the Theorem 3.5 Dirichlet forms, being coercive, closed forms, generate pairs of strongly continuous, contractive semigroups. In order to be sure, however, that these semigroups are associated to some Markov process we must be able to implement them by means of explicit transition functions: the following result shows that to realize this program we have to request a particular regularity condition to our Dirichlet forms. Here $C_0(\mathbf{R}^n)$ is the set of the continuous functions with compact support defined on \mathbf{R}^n .

Definition 3.7. A Dirichlet form $(\mathcal{E}, D(\mathcal{E}))$ on $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ is regular if the set $C_0(\mathbf{R}^n) \cap D(\mathcal{E})$ is dense both in $D(\mathcal{E})$ with respect to its norm $\|\cdot\|_1$, and in $C_0(\mathbf{R}^n)$ with respect to its sup-norm $\|\cdot\|_\infty$.

Theorem 3.8. Take a regular Dirichlet form $(\mathcal{E}, D(\mathcal{E}))$ on $\mathcal{L}^2(\mathbf{R}^n, d\mu)$, with its associated strongly continuous semigroups $(T_t)_{t \geq 0}$ and $(\tilde{T}_t)_{t \geq 0}$: then there are two time-homogeneous transition functions p_t and \tilde{p}_t on $(\mathbf{R}^n, \mathcal{B}(\mathbf{R}^n))$ such that μ -a.s.

$$[T_t f](x) = \int f(y) p_t(x, dy) \quad [\tilde{T}_t f](x) = \int f(y) \tilde{p}_t(x, dy)$$

for every $t \geq 0$ and $f \in \mathcal{L}^2(\mathbf{R}^n, d\mu)$.

PROOF. See [18], Chap. IV. □

By means of Theorem 3.8 we can then associate to a regular Dirichlet form two Markov processes $(X_t)_{t \geq 0}$ and $(\tilde{X}_t)_{t \geq 0}$ defined on \mathbf{R}^n – but for an arbitrary initial distribution – respectively by p_t and \tilde{p}_t , and enjoying several useful properties such as right continuity with left limit and strong Markov property (for details see [17, 18, 23]). The transition functions p_t and \tilde{p}_t , however, could in general be *sub-Markovian*, namely we could have $p_t(x, \mathbf{R}^n) \leq 1$ for some $x \in \mathbf{R}^n$. To avoid this it can be easily proved, by a general property of strongly continuous semigroups [25], that if the constant function $u_1 = 1$ belongs to $D(L)$ and $D(\tilde{L})$, then we find $p_t(x, \mathbf{R}^n) = \tilde{p}_t(x, \mathbf{R}^n) = 1$ for every $x \in \mathbf{R}^n$ if and only if $Lu_1 = \tilde{L}u_1 = 0$. In this case, moreover, we also have that μ is an invariant measure for both p_t and \tilde{p}_t . Indeed, since p_t and \tilde{p}_t are *in duality* with respect to μ , namely

$$\iint f(x)g(y) p_t(x, dy)\mu(dx) = \iint f(y)g(x) \tilde{p}_t(x, dy)\mu(dx) \quad (12)$$

as we easily deduce from $\tilde{T}_t = T_t^\dagger$, by taking $f(x) = 1$ and $g(y) = \mathbf{1}_B(y)$ for $B \in \mathcal{B}(\mathbf{R}^n)$ we get

$$\begin{aligned} \int p_t(x, B)\mu(dx) &= \iint \mathbf{1}_B(y)p_t(x, dy)\mu(dx) = \iint \mathbf{1}_B(x)\tilde{p}_t(x, dy)\mu(dx) \\ &= \int \mathbf{1}_B(x)\tilde{p}_t(x, \mathbf{R}^n)\mu(dx) = \int \mathbf{1}_B(x)\mu(dx) = \mu(B) \end{aligned}$$

namely μ is invariant. The same proof can be adapted to \tilde{p}_t . Finally under special condition it is also possible to associate to $(\mathcal{E}, D(\mathcal{E}))$ a *single* bilateral Markov process $X = (X_t)_{t \in \mathbf{R}}$ obtained by sewing together $(X_t)_{t \geq 0}$ and $(\tilde{X}_t)_{t \geq 0}$. This occurs in particular when μ is an invariant probability measure. In this case in fact we first define the canonical process X_t with $t \in \mathbf{R}$ and its distribution \mathbb{P}_μ as the Kolmogorov extension of

$$\begin{aligned} \mathbb{P}_\mu(X_{t_1} \in B_1) &= \mu(B_1) \\ \mathbb{P}_\mu(X_{t_1} \in B_1, \dots, X_{t_k} \in B_k) &= \int_{B_1 \times \dots \times B_k} p_{t_k - t_{k-1}}(x_{k-1}, dx_k) \dots \\ &\quad \dots p_{t_2 - t_1}(x_1, dx_2)\mu(dx_1) \end{aligned} \quad (13)$$

for $B_k \in \mathcal{B}(\mathbf{R}^n)$, $k \in \mathbf{N}$, and $t_1 \leq t_2 \leq \dots \leq t_k \leq \dots$, and then we show that $(X_t)_{t \in \mathbf{R}}$ is a Markov process with respect to \mathbb{P}_μ , having p_t and \tilde{p}_t respectively as its forward and backward transition functions. Actually it is straightforward to prove that $(X_t)_{t \in \mathbf{R}}$ is a Markov process and that p_t is the forward transition function for it. As for \tilde{p}_t we have instead to check that

$$\mathbb{P}_\mu(X_{s-t} \in B | X_s = x) = \mathbb{E}_\mu\{\mathbf{1}_B(X_{s-t}) | X_s = x\} = \tilde{p}_t(x, B) \quad (14)$$

for every Borel set B , $s \in \mathbf{R}$ and $t \geq 0$. To this effect it will be enough to remark that, for every B_1 and B_2 , from (13) and (12) we have

$$\begin{aligned} &\mathbb{E}_\mu\{\mathbf{1}_{B_2}(X_s)\mathbb{E}_\mu\{\mathbf{1}_{B_1}(X_{s-t}) | X_s\}\} \\ &= \mathbb{E}_\mu\{\mathbf{1}_{B_2 \times B_1}(X_s, X_{s-t})\} = \mathbb{P}_\mu(X_{s-t} \in B_1, X_s \in B_2) \\ &= \iint \mathbf{1}_{B_1}(x)\mathbf{1}_{B_2}(y)p_t(x, dy)\mu(dx) = \iint \mathbf{1}_{B_1}(y)\mathbf{1}_{B_2}(x)\tilde{p}_t(x, dy)\mu(dx_0) \\ &= \int \mathbf{1}_{B_2}(x)\tilde{p}_t(x, B_1)\mu(dx) = \mathbb{E}_\mu\{\mathbf{1}_{B_2}(X_s)\tilde{p}_t(X_s, B_1)\} \end{aligned}$$

which proves (14). It can be seen moreover [22] that this unifying procedure can be adopted even when the invariant measure is not a probability. As a consequence, according to Theorem 3.8, the semigroup generators L and \tilde{L} on $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ derived through (9) and (10) from a regular Dirichlet form $(\mathcal{E}, D(\mathcal{E}))$ can be considered as the forward and backward generators of a single, bilateral Markov process $(X_t)_{t \in \mathbf{R}}$ when $Lu_1 = \tilde{L}u_1 = 0$.

Let us conclude this survey with a few remarks about how to check that Dirichlet forms actually are regular: if the space $C_0^\infty(\mathbf{R}^n)$ of the infinitely derivable real functions with compact support is contained in $D(\mathcal{E})$, it is possible to prove [18] that for a symmetric Dirichlet form $(\mathcal{E}, D(\mathcal{E}))$ on $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ the following *Beurling-Deny formula* holds for every $f, g \in C_0^\infty(\mathbf{R}^n)$:

$$\begin{aligned} \mathcal{E}(f, g) = & \sum_{i,j=1}^n \int \partial_i f(x) \partial_j g(x) \mu^{ij}(dx) + \int f(x) g(x) k(dx) \\ & + \iint_{x \neq z} [f(x) - f(z)][g(x) - g(z)] J(dx, dz) \end{aligned} \quad (15)$$

where $k(dx)$ is a positive Radon measure on \mathbf{R}^n (*killing measure*), $J(dx, dz)$ is a symmetric, positive Radon measure defined on $\mathbf{R}^n \times \mathbf{R}^n$ for $x \neq z$ (*jump measure*) and such that for every $f \in C_0^\infty(\mathbf{R}^n)$

$$\iint_{x \neq z} |f(x) - f(z)|^2 J(dx, dz) < \infty \quad (16)$$

and $\mu^{ij}(dx)$ for $i, j = 1, \dots, n$ are positive Radon measures on \mathbf{R}^n (*diffusion measures*) such that for every compact subset $B \subseteq \mathbf{R}^n$ and $b \in \mathbf{R}^n$ it results

$$\mu^{ij}(B) = \mu^{ji}(B) \quad \sum_{i,j=1}^n b_i b_j \mu^{ij}(B) \geq 0 \quad (17)$$

Proposition 3.9. *Take a closable, bilinear form $(\mathcal{E}, D(\mathcal{E}))$ on $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ with $D(\mathcal{E}) = C_0^\infty(\mathbf{R}^n)$: if \mathcal{E} satisfies the Beurling-Deny formula (15), then its closure $(\bar{\mathcal{E}}, D(\bar{\mathcal{E}}))$ is a regular Dirichlet form.*

PROOF. See [18], Chap II □

Taken together the Theorem 3.8 and the Proposition 3.9 imply that when we want to know if there is a Markov process associated to a given generator L , essentially we must first consider the bilinear forms (9) and (10), and then check that the Beurling-Deny formula (15) holds.

4 Lévy Processes

The processes with independent increments constitute an important class of Markov processes, and among them the Lévy processes [9, 10, 11, 12] are of particular relevance and are today widely applied in a variety of fields [8, 14]; they have also been introduced in the larger context of quantum probability [24]. Actually these processes are also time-homogeneous and hence they can be identified by means of a transition function p_t only. They are stochastically continuous with independent and stationary increments, and they include many families of well known processes as the

Poisson, the Cauchy, the Student, the Variance-Gamma and, of course, the Wiener process which is the unique Gaussian process, with *a.s.* continuous paths. The Lévy processes are Feller processes and – if integrable with zero expectation – they are also martingales. In general, however, they always are semi-martingales, so that in any case they can be used as integrators in Itô integrals [11]. It is finally important to remark that between the Lévy processes and the infinite divisible distributions [9] there is a one-to-one correspondence.

Given a filtered, complete probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t \geq 0}, \mathbb{P})$, an \mathbf{R}^n valued process $(Z_t)_{t \geq 0}$ is said to be a *Lévy process* if it is adapted and

1. $Z_0 = 0$ *a.s.*
2. $Z_t - Z_s$ is independent from \mathcal{F}_s , for $0 \leq s \leq t$.
3. $Z_{t+h} - Z_t = Z_{s+h} - Z_s$ in distribution, for every $s, t, h \geq 0$.
4. Z_t is stochastically continuous, i.e. $Z_{t+\Delta t} - Z_t \rightarrow 0$ in probability as $\Delta t \rightarrow 0$.

It is possible to prove [9, 11] that every Lévy process Z_t admits a version – which still is a Lévy process – with \mathbb{P} -a.s. *cadlag* (continuous on the right with left limits) paths. To describe how the random discontinuities of its trajectories are distributed the *Lévy measure* is introduced, a concept that however could also be defined independently: a positive measure $\ell(dx)$ on $(\mathbf{R}_0^n, \mathcal{B}(\mathbf{R}_0^n))$ (here $\mathbf{R}_0^n = \mathbf{R}^n - \{0\}$) is a Lévy measure if

$$\int_{x \neq 0} (|x|^2 \wedge 1) \ell(dx) < \infty \quad (18)$$

When associated – as we will see in a moment – to a Lévy process Z_t , $\ell(dx)$ represents the average number of jumps with size between x and $x + dx$ performed in a unit time. If we in fact represent a possible jump size at time t by

$$\Delta_t Z := Z_t - Z_{t-} \quad Z_{t-} := \lim_{s \uparrow t} Z_s$$

and we take $\Lambda \in \mathcal{B}(\mathbf{R}^n)$ such that 0 does not belong to its closure $\bar{\Lambda}$, we can define for $t > 0$ the process

$$N_t^\Lambda(\omega) := \{\text{number of jumps with size } \Delta_s Z(\omega) \in \Lambda, \text{ for } 0 < s \leq t\} \quad (19)$$

with $N_0^\Lambda = 0$, and we have the following result

Proposition 4.1. *If Z_t is a Lévy process, then N_t^Λ is a Poisson process with parameter $\nu(\Lambda) = \mathbb{E}\{N_1^\Lambda\}$.*

PROOF. See [11] □

The Poisson parameter $\nu(\Lambda)$, on the other hand, turns out to be an additive set function which can be extended to a measure ℓ on $(\mathbf{R}_0^n, \mathcal{B}(\mathbf{R}_0^n))$, and it can be proved that it satisfies (18), namely that it is a *Lévy measure* associated to Z_t . This measure ℓ plays a relevant role among the few parameters that completely characterize a Lévy process according to the following *Lévy-Khintchin formula* [9]

Theorem 4.2. *Let $(Z_t)_{t \geq 0}$ a Lévy process. Then its logarithmic characteristic $\eta(u) := \log \mathbb{E}\{e^{iu \cdot Z_1}\}$ satisfies*

$$\eta(u) = -\frac{1}{2}u \cdot Au + i\gamma \cdot u + \int_{y \neq 0} [e^{iu \cdot y} - 1 - i(u \cdot y) \mathbf{1}_{B_1}(y)] \ell(dy) \quad (20)$$

where $A = \|\alpha_{ij}\|$ is a symmetric non negative-definite $n \times n$ matrix, $\gamma \in \mathbf{R}^n$, $B_1 = \{y \in \mathbf{R}^n : |y| \leq 1\}$ and $\ell(dy)$ is a Lévy measure. This representation of η by means of the triplet (A, ℓ, γ) is unique. Viceversa, if A is a symmetric non negative-definite $n \times n$ matrix, $\gamma \in \mathbf{R}^n$ and ℓ is a Lévy measure, then (20) is the logarithmic characteristic associated to a unique (in distribution) Lévy process $(Z_t)_{t \geq 0}$.

The triplet (A, ℓ, γ) is usually called the *generating triplet* of $(Z_t)_{t \geq 0}$. The laws \mathbb{P}_{Z_1} with characteristic functions $\varphi(u) = e^{\eta(u)} = \mathbb{E}\{e^{iu \cdot Z_1}\}$ turn out to be *infinitely divisible (id)* [9], and as a consequence φ^t still is the characteristic function of some other *id* law for every $t > 0$. More precisely, if φ_t is the characteristic function of \mathbb{P}_{Z_t} for $t \geq 0$, namely $\varphi_t(u) = \mathbb{E}\{e^{iu \cdot Z_t}\}$, then it is easy to show that $\varphi_t = \varphi^t$. This result provides a one-to-one correspondence between the Lévy processes and the *id* laws [9, 12] in such a way that every Lévy process is in fact uniquely determined by its *id* distribution at a unique instant, usually at $t = 1$.

We conclude this section with the explicit expressions of the infinitesimal generator $(L_0, D(L_0))$ and of the Dirichlet form $(\mathcal{E}_0, D(\mathcal{E}_0))$ associated to a symmetric Lévy process Z_t in $\mathcal{L}^2(\mathbf{R}^n, dx)$. The generator L_0 is a pseudo-differential operator with symbol η [10, 11] namely

$$[L_0 f](x) = \frac{-1}{(2\pi)^n} \int e^{iux} \hat{f}(u) \eta(u) du \quad (21)$$

where \hat{f} is the Fourier transform of f , and $D(L_0)$ is the set of the $f \in \mathcal{L}^2(\mathbf{R}^n, dx)$ such that

$$\int |\hat{f}(u)|^2 |\eta(u)|^2 du < \infty \quad (22)$$

From (22) it can be proved that actually the Schwarz space $\mathcal{S}(\mathbf{R}^n)$ is a subset of $D(L_0)$, and when $f \in \mathcal{S}(\mathbf{R}^n)$ the infinitesimal generator of Z_t takes the more explicit form

$$[L_0 f](x) = \frac{1}{2} \nabla \cdot A \nabla f(x) + \int_{y \neq 0} [\delta_y^2 f](x) \ell(dy) \quad (23)$$

where $A = \|\alpha_{ij}\|$ is the symmetric, positive definite matrix, and ℓ is the Levy measure of the generating triplet of Z_t , and we adopted the shorthand notations

$$\begin{aligned} [\delta_y f](x) &:= f(x+y) - f(x) \\ [\delta_y^2 f](x) &:= f(x+y) - f(x) - y \cdot \nabla f(x) \mathbf{1}_{B_1}(y) \end{aligned}$$

with $B_1 = \{y \in \mathbf{R}^n : |y| \leq 1\}$. It is also easy to see then that

$$\delta_y(fg) = g\delta_y f + f\delta_y g + \delta_y f \delta_y g \quad (24)$$

$$\delta_y^2(fg) = g\delta_y^2 f + f\delta_y^2 g + \delta_y f \delta_y g \quad (25)$$

If the Lévy process is also rotationally invariant then we have $\alpha_{ij} = \alpha\delta_{ij}$ and (23) is reduced to

$$[L_0f](x) = \frac{\alpha}{2} \nabla^2 f(x) + \int_{y \neq 0} [\delta_y^2 f](x) \ell(dy) \quad (26)$$

As for the bilinear form associated to our symmetric Lévy process Z_t with generator $(L_0, D(L_0))$, namely

$$\mathcal{E}_0(f, g) = -\langle L_0f, g \rangle = - \int g(x)[L_0f](x) dx$$

we have [17] on $D(L_0)$

$$\mathcal{E}_0(f, g) = - \int \nabla g(x) \cdot A \nabla f(x) dx - \frac{1}{2} \int \int_{y \neq 0} [\delta_y f](x) [\delta_y g](x) \ell(dy) dx \quad (27)$$

This last expression can also be extended to a $D(\mathcal{E}_0) \supseteq D(L_0)$, the set of the $f \in \mathcal{L}^2(\mathbf{R}^n, dx)$ such that

$$\int \nabla f(x) \cdot A \nabla f(x) dx + \int \int_{y \neq 0} |[\delta_y f](x)|^2 \ell(dy) dx < \infty \quad (28)$$

5 Doob transformations

We turn now to the discussion of the association of a generalized Schrödinger equations to our Markov processes. Let $(X_t)_{t \in \mathbf{R}}$ be a time-homogeneous, bilateral Markov process with infinitesimal forward and backward generators $(L, D(L))$ and $(\tilde{L}, D(\tilde{L}))$. We suppose that

1. X_t has an *a.c.* invariant measure $\mu(dx) = \rho(x)dx$;
2. $\rho(x) > 0$ *a.s.* with respect to the Lebesgue measure, so that $\mu(dx)$ is equivalent to the Lebesgue measure;
3. the set $D(L) \cap D(\tilde{L})$ is dense in $\mathcal{L}^2(\mathbf{R}^n, d\mu)$.

As already stated in the Section 2 the invariant measure μ is not necessarily required to be a probability measure: it will be made clear in a few subsequent examples about the plane waves that we will indeed consider also cases where the invariant measure is rather σ -finite, as the Lebesgue measure on \mathbf{R}^n . From our hypothesis 3 it also follows [25] that both $(T_t)_{t \geq 0}$ and $(\tilde{T}_t)_{t \geq 0}$ are *strongly continuous* semigroups in $\mathcal{L}^2(\mathbf{R}^n, d\mu)$, and that

$$\tilde{L} = L^\dagger \quad (29)$$

If then Y_t is the space-time version of X_t , its infinitesimal forward and backward generators L^Y and \tilde{L}^Y are defined on $\mathcal{L}^2(\mathbf{R}^{n+1}, d\mu dt)$, and it can be easily shown that

$$L^Y = L + \partial_t \quad \tilde{L}^Y = \tilde{L} - \partial_t \quad (30)$$

with $D(L^Y) = D(L) \otimes \mathcal{H}^1$ and $D(\tilde{L}^Y) = D(\tilde{L}) \otimes \mathcal{H}^1$, where \mathcal{H}^1 is the space of the absolutely continuous functions of t with a square integrable derivative. The result (30) is apparently connected to the fact that the infinitesimal generator of the translation semigroup – namely the semigroup of the degenerate Markov process τ_t – is the time derivative [25]. Remark that if the hypothesis 3. is satisfied by L and \tilde{L} , then it will hold also for L^Y and \tilde{L}^Y , and we will have

$$\tilde{L}^Y = (L^Y)^\dagger \quad (31)$$

All our generators L, \tilde{L}, L^Y and \tilde{L}^Y can now be also naturally extended to the respective spaces $\mathcal{L}_C^2(\mathbf{R}^n, d\mu)$ and $\mathcal{L}_C^2(\mathbf{R}^{n+1}, d\mu dt)$ of the complex valued functions, where they are still densely defined and closed, while the relations (29) and (31) are preserved. Moreover, in order to make sure that the Hamiltonian operators that we will introduce later are bounded from below, we also add a fourth hypothesis:

4. $\exists C \in \mathbf{R}$ such that for every ϕ in $D(L)$

$$-\Re\langle\phi, L\phi\rangle_\mu + \Im\langle\phi, L\phi\rangle_\mu \geq C \|\phi\|_\mu \quad (32)$$

Remark however that if X_t is a μ -symmetric process, namely if L turns out to be self-adjoint in $\mathcal{L}_C^2(\mathbf{R}^n, d\mu)$, then $\Im\langle\phi, L\phi\rangle_\mu$ vanishes and the condition (32) becomes

$$-\langle\phi, L\phi\rangle_\mu \geq C \|\phi\|_\mu$$

which is automatically satisfied because L is the generator of a contraction semigroup so that [25] $\langle\phi, L\phi\rangle_\mu \leq 0$, and it will be enough to take $C = 0$. As a consequence the hypothesis 4 is always satisfied by μ -symmetric processes. The relevance of this fourth condition will be made clear in the following, and it lies mainly in the fact that for a given symmetric, bounded from below operator $(H_0, D(H_0))$ on a Hilbert space \mathfrak{H} , there always exists [26] a *self-adjoint* operator $(H, D(H))$ bounded from below such that $D(H_0) \subset D(H)$, and that for every $v \in D(H_0)$, $Hv = H_0v$. This operator H is usually called the *Friedrichs extension* of H_0 .

Proposition 5.1. *If X_t is a time-homogeneous Markov process satisfying the hypotheses 1-4, then the operator in $\mathcal{L}_C^2(\mathbf{R}^{n+1}, d\mu dt)$*

$$K^Y := -\frac{\tilde{L}^Y + iL^Y}{i+1} = -\frac{L^Y + \tilde{L}^Y}{2} + \frac{L^Y - \tilde{L}^Y}{2i} \quad (33)$$

defined on $D(K^Y) := D(L^Y) \cap D(\tilde{L}^Y)$, is symmetric.

PROOF. From the hypothesis 3. we deduce that K^Y is densely defined, while the symmetry easily follows from (31). \square

We can also introduce in $\mathcal{L}_C^2(\mathbf{R}^n, d\mu)$ the reduced operator

$$K := -\frac{\tilde{L} + iL}{i+1} = -\frac{L + \tilde{L}}{2} + \frac{L - \tilde{L}}{2i} \quad (34)$$

defined on $D(K) := D(L) \cap D(\tilde{L})$, and prove in a similar way that it is symmetric. Remark how the existence of both a forward and a backward generator is instrumental here in the definition of our symmetric operators K and K^Y . It should also be said, however, that starting from our generators we could define several different symmetric operators, our present choice being dictated mainly by an analogy with the Gaussian case, and by our interest in preserving the presence of the time derivatives ∂_t in the final operators.

Given now an arbitrary real function $S(x)$ (a change in it would simply be tantamount to a gauge transformation) and a constant $E \in \mathbf{R}$, we first define the *wave functions*

$$\psi(x) := \sqrt{\rho(x)} e^{iS(x)} \quad \Psi(x, t) := \psi(x) e^{-iEt} \quad (35)$$

and then we remark that the operators

$$\begin{aligned} U_\Psi &: f \in \mathcal{L}_C^2(\mathbf{R}^{n+1}, d\mu dt) \longrightarrow f\Psi \in \mathcal{L}_C^2(\mathbf{R}^{n+1}, dx dt) \\ U_\psi &: f \in \mathcal{L}_C^2(\mathbf{R}^n, d\mu) \longrightarrow f\psi \in \mathcal{L}_C^2(\mathbf{R}^n, dx) \end{aligned} \quad (36)$$

are unitary with

$$U_\Psi^\dagger = U_\Psi^{-1} = U_{\frac{1}{\Psi}} \quad U_\psi^\dagger = U_\psi^{-1} = U_{\frac{1}{\psi}}$$

By means of these we can now introduce the operators

$$K_\Psi^Y = U_\Psi K^Y U_\Psi^{-1} \quad K_\psi = U_\psi K U_\psi^{-1} \quad (37)$$

acting respectively on $\mathcal{L}_C^2(\mathbf{R}^{n+1}, dx dt)$ and $\mathcal{L}_C^2(\mathbf{R}^n, dx)$ with $D(K_\Psi^Y) = U_\Psi D(K^Y)$ and $D(K_\psi) = U_\psi D(K)$. These unitary transformations are reminiscent of the well known *Doob transformation* [23, 27, 28] which is applied to the infinitesimal generators L of Markov processes for a real, positive Ψ in the domain of L with $L\Psi = 0$. Our transformation could also be defined in a more general way [23], but in fact (37) turns out to be well suited to our purposes so that we will continue to call it Doob transformation, while K_Ψ^Y and K_ψ will be called the Doob transforms of K^Y and K .

Proposition 5.2. *The operator K_Ψ^Y can be written as*

$$K_\Psi^Y = H_0 \otimes I_t - iI_0 \otimes \partial_t$$

where I_0 and I_t are the identity operators respectively on the x and t variables, while

$$H_0 = K_\psi + E \quad (38)$$

turns out to be a symmetric and bounded from below operator in $\mathcal{L}_C^2(\mathbf{R}^n, dx)$. We also have that ψ is an eigenvector with eigenvalue E of the Friedrichs extension H of H_0

$$H\psi(x) = E\psi(x) \quad (39)$$

and that the function $\Psi(x, t)$ is a strong solution of

$$i\partial_t \Psi(x, t) = H\Psi(x, t) \quad (40)$$

being for every $t > 0$ also a solution of (39).

PROOF. From (30) we have for $\phi \in D(K_\Psi^Y)$

$$\begin{aligned} K_\Psi^Y \phi &= -\Psi \frac{L + \tilde{L}}{2} \frac{\phi}{\Psi} - i\Psi \partial_t \frac{\phi}{\Psi} + \Psi \frac{L - \tilde{L}}{2i} \frac{\phi}{\Psi} \\ &= -\psi \left(\frac{L + \tilde{L}}{2} - \frac{L - \tilde{L}}{2i} \right) \frac{\phi}{\psi} + E\phi - i\partial_t \phi = (H_0 \otimes I_t)\phi - i(I_0 \otimes \partial_t)\phi \end{aligned}$$

From the hypothesis 4. we can see now that H_0 is bounded from below, while from the hypothesis 3. we deduce that it is densely defined, and from (29) that it is symmetric: then its Friedrichs extension H exists and is self-adjoint. Moreover the constant function $\phi_1 = 1$ is an element of $D(L) \cap D(\tilde{L})$ and from (12) and hypothesis 1 it is easy to see that $L\phi_1 = \tilde{L}\phi_1 = 0$. As a consequence we have from (38) that $\psi \in D(H_0)$, and that $H_0\psi = E\psi$: namely ψ is an eigenfunction of H_0 corresponding to the eigenvalue E . It is then straightforward to prove (40). \square

The Friedrichs extension H of H_0 will be called in the following the *Hamiltonian operator* associated to the Markov process X_t , and the equation (40) will take the name of *generalized Schrödinger equation*. Remark that if in particular X_t is a μ -symmetric process, namely if L is self-adjoint, then we simply have

$$K^Y = -L - i\partial_t \quad K = -L \quad H_0 = -U_\psi L U_\psi^{-1} + E \quad (41)$$

so that H_0 itself is self-adjoint and hence coincides with H . This however is not the case for every Markov process $X(t)$ that we can consider within our initial hypotheses.

In conclusion we have shown that from every Markov process X_t obeying our four initial hypotheses we can always derive a self-adjoint Hamiltonian H and a corresponding generalized Schrödinger equation (40). In this scheme the process X_t is associated to a particular stationary solution Ψ of (40) in such a way that $|\Psi|^2$ coincides with the invariant measure of X_t . Vice versa it would be interesting to be able to trace back a suitable Markov process X_t from a solution Ψ – at least from a *stationary* solution – of (40) with a self-adjoint Hamiltonian. In fact, even when from a given Hamiltonian H and a stationary solution Ψ of (40) we can manage – by treading back along the path mapped in this section – to get a semigroup L , we are still left with the problem of checking that the minimal conditions are met in order to be sure that there is a Markov process X_t associated to L . In this endeavor the previous discussion about the Dirichlet forms developed in the Section 3 will turn out to be instrumental as it will be made clear in the following.

6 Stochastic mechanics

Let us begin by remembering that the names we gave to H and to the equation (40) at the end of the previous section are justified by the fact that when X_t is a solution

of the Itô *SDE* (Stochastic Differential Equation)

$$dX_t = b(X_t)dt + dW_t \quad (42)$$

where W_t is a Wiener process, then H turns out to be the Hamiltonian operator appearing in the usual Schrödinger equation of quantum mechanics. To show how this works we will briefly review here this well known result in the less familiar framework of the Doob transformations [19, 20] because – at variance with the original Nelson *stochastic mechanics* – this procedure allows a derivation of the Schrödinger equation without introducing an explicit *dynamics* that, at present, is still not completely ironed out in the more general context of the Lévy processes.

Let us start by considering the operator

$$L_0 := \frac{1}{2} \nabla^2$$

with $D(L_0)$ the set of all the functions f that, along with their first and second generalized derivatives, belong $\mathcal{L}^2(\mathbf{R}^n, dx)$. It is well known that $(L_0, D(L_0))$ is the infinitesimal generator of a Wiener process. If now we take $\phi \in D(L_0)$ such that

$$\int_{\mathbf{R}^n} \phi^2(x) dx = 1, \quad \phi \neq 0 \quad a.s. \text{ in } dx$$

we can define in $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ with $\mu(dx) = \rho(x)dx = \phi^2(x)dx$ a second operator

$$Lf := \frac{L_0(\phi f) - f L_0 \phi}{\phi} \quad (43)$$

where $D(L) := C_0^\infty(\mathbf{R}^n)$ is the set of infinitely derivable functions on \mathbf{R}^n with bounded support. It is straightforward now to see that L is correctly defined [22], and that (43) can be recast in the form

$$Lf = \frac{\nabla \phi}{\phi} \cdot \nabla f + \frac{1}{2} \nabla^2 f = b \cdot \nabla f + \frac{1}{2} \nabla^2 f \quad b = \frac{\nabla \phi}{\phi} \quad (44)$$

which on the other hand is typical for the generators of a process satisfying the *SDE* (42). At first sight this seems to imply directly that to every given ϕ we can always associate a Markov process (weak) solution of the *SDE* (42) with b defined as in (44), but this could actually be deceptive because this association is indeed contingent on the properties of the function b , and hence of ϕ . To be more precise: if we know that the equation (42) has a solution X_t , then its generator certainly has the form (44); but vice versa if an operator (44) – or a *SDE* (42) – is given with an arbitrary b , we can not in general be sure that a corresponding Markov process X_t solution of (42) does in fact exist, albeit in a weak sense. In the light of these remarks it is important then to be able to prove, by means of the Dirichlet forms, that for L and b defined as in (44) we can always find a Markov process solution of (42).

Theorem 6.1. *The operator $(L, D(L))$ defined in (44) is closable and its closure $(\bar{L}, D(\bar{L}))$ is a self-adjoint, negative definite operator which is the infinitesimal generator of a Markov process $(X_t)_{t \in \mathbf{R}}$ (weak) solution of (42). The measure $\mu(dx)$ is invariant for this Markov process.*

PROOF. Let us consider on $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ the bilinear form

$$\mathcal{E}(f, g) := -\langle Lf, g \rangle_\mu$$

with $D(\mathcal{E}) := C_0^\infty(\mathbf{R}^n)$. For $f, g \in D(\mathcal{E})$ with an integration by parts we get

$$\begin{aligned} \mathcal{E}(f, g) &= -\frac{1}{2} \int_{\mathbf{R}^n} g(x) \phi(x) \nabla^2(\phi f)(x) dx + \frac{1}{2} \int_{\mathbf{R}^n} g(x) f(x) \phi(x) \nabla^2 \phi(x) dx \\ &= -\frac{1}{2} \int_{\mathbf{R}^n} g(x) \phi^2(x) \nabla^2 f(x) dx - \int_{\mathbf{R}^n} g(x) \phi(x) \nabla f(x) \cdot \nabla \phi(x) dx \\ &= \int_{\mathbf{R}^n} \phi^2(x) \nabla g(x) \cdot \nabla f(x) dx \end{aligned}$$

namely our form satisfies the Beurling-Deny formula (15) with vanishing jump and killing measures, and with the condition (17) trivially satisfied. As a consequence \mathcal{E} is symmetric and positive definite, so that also $-L$ is symmetric and positive definite and then is also closable [26]. Hence by Proposition 3.3 $(\mathcal{E}, D(\mathcal{E}))$ is closable and from the Proposition 3.9 its closure $(\bar{\mathcal{E}}, D(\bar{\mathcal{E}}))$ is a symmetric, regular Dirichlet form which from Theorem 3.5 is associated to a self-adjoint, infinitesimal generator $(\bar{L}, D(\bar{L}))$. Of course $(\bar{L}, D(\bar{L}))$ itself turns out [26] to be the closure of $(L, D(L))$.

This \bar{L} generates now a unique, bilateral Markov process $(X_t)_{t \in \mathbf{R}}$ on $(\mathbf{R}^n, \mathcal{B}(\mathbf{R}^n))$ having μ as its invariant measure when the conditions discussed in the remarks following the Theorem 3.8 are met. In this context we are then left just with the task of showing that the constant function $f_1(x) = 1$ belongs to $D(\bar{L})$ and that $\bar{L}f_1 = 0$. In fact for every $f \in C_0^\infty$ dense in $\mathcal{L}^2(\mathbf{R}^n, d\mu)$, with an integration by parts we have

$$\begin{aligned} \langle f_1, \bar{L}f \rangle_\mu &= \int_{\mathbf{R}^n} [\bar{L}f] \phi^2 dx = \int_{\mathbf{R}^n} [Lf] \phi^2 dx \\ &= \frac{1}{2} \int_{\mathbf{R}^n} \phi \nabla^2(f\phi) dx - \frac{1}{2} \int_{\mathbf{R}^n} f \phi \nabla^2 \phi dx \\ &= \frac{1}{2} \int_{\mathbf{R}^n} f \phi \nabla^2 \phi dx - \frac{1}{2} \int_{\mathbf{R}^n} f \phi \nabla^2 \phi dx = 0 \end{aligned}$$

Being \bar{L} self-adjoint this implies first that $f_1 \in D(\bar{L})$, and that $\langle \bar{L}f_1, f \rangle_\mu = 0$ for every $f \in C_0^\infty$ dense in $\mathcal{L}^2(\mathbf{R}^n, d\mu)$, and then that $\bar{L}f_1 = 0$. \square

Since the process $(X_t)_{t \in \mathbf{R}}$ obtained from L_0 in the Theorem 6.1 satisfies all the hypotheses 1-4 with $\rho(x) = \phi^2(x)$, we can now go on looking for the Hamiltonians

produced by the Doob transformations. Take first the wave functions (35) with arbitrary $E \in \mathbf{R}$ and $S(x) = 0$, namely

$$\psi(x) = \phi(x) \quad \Psi(x, t) = e^{-iEt} \phi(x) \quad (45)$$

Since \bar{L} is self-adjoint, by applying (41) we easily find as Hamiltonian associated to X_t by the Doob transformation the operator

$$H := -\frac{1}{2}\nabla^2 + V(x) \quad (46)$$

where the potential function (defined up to a constant additive factor) is

$$V(x) = \frac{\nabla^2 \phi(x)}{2\phi(x)} + E \quad (47)$$

namely the potential of a Schrödinger equation admitting ϕ as eigenvector with eigenvalue E as it is immediately seen by rewriting (59) as

$$-\frac{1}{2}\nabla^2 \phi + V\phi = E\phi$$

In this way the Doob transformation associates a Markov process to every stationary solution (45) of the Schrödinger equation

$$i\partial_t \Psi = H\Psi \quad (48)$$

with Hamiltonian (46). When on the other hand we consider a non vanishing $S(x)$ then our wave functions show the complete form (35), and starting again from (41) a slightly longer calculation shows that the Hamiltonian now is

$$H = \frac{1}{2}(i\nabla + \nabla S)^2 + V$$

with $V(x)$ always defined as in (59): in other words in this case from ϕ and S we get both a scalar and a vector potential [29], namely a model where the interactions are produced by generalized electromagnetic potentials.

Similar results can be obtained by initially choosing a constant function $\phi(x) = 1$ and $S(x) = p \cdot x$ so that

$$\psi(x) = e^{ip \cdot x} \quad \Psi(x, t) = e^{ip \cdot x - iEt}$$

namely the wave function of a plane wave. In this case however instead of (43) we have to take

$$Lf := L_0 f + p \cdot \nabla f = \frac{1}{2}\nabla^2 f + p \cdot \nabla f$$

which is still of the form (44), albeit with a constant $b(x) = p$. Since this L is no longer self-adjoint in $\mathcal{L}(\mathbf{R}^2, dx)$ because, with an integration by parts, we find

$$L^\dagger = \tilde{L} = \frac{1}{2}\nabla^2 f - p \cdot \nabla f$$

we now get from (34) and (37)

$$Kf = -\frac{1}{2}\nabla^2 f - ip \cdot \nabla f \quad K_\psi f = -\frac{1}{2}\nabla^2 f - \frac{p^2}{2}f$$

and then finally – by choosing, as usual, $E = p^2/2$ – we obtain from (38)

$$H = \frac{1}{2}\nabla^2$$

which is the Hamiltonian of the Schrödinger equation (48) in its free form. Remark that since $b(x) = p$ the resulting Markov process associated to Ψ now simply is a Wiener process plus a constant drift, but, at variance with the previous cases, we no longer have normalizable stationary solutions of (48), because $\phi^2(x)dx = dx$ defines an invariant measure which is the Lebesgue measure and not a probability: in other words our Markov process X_t will be an improper one in the sense outlined in the Section 2.

7 Lévy-Schrödinger Equation

In this section we will focus our attention on a form of the generalized Schrödinger equation (40) which, without being the most general one, is less particular than that discussed in the Section 6: namely the Lévy-Schrödinger equation already introduced in a few previous papers [1] where the Hamiltonian operator was found to be

$$H = -L_0 + V, \quad D(H) = D(L_0) \cap D(V) \quad (49)$$

with $(L_0, D(L_0))$ infinitesimal generator of a symmetric Lévy process taking values in \mathbf{R}^n , and V a measurable real function defined on \mathbf{R}^n that makes the operator $(H, D(H))$ self-adjoint and bounded from below. We have already seen in (21) and (23) how the generator $(L_0, D(L_0))$ of a Lévy process actually operates. We add here that when the Lévy process is symmetric its logarithmic characteristic $\eta(u)$ is a real function, and hence from (21) we easily have that $(L_0, D(L_0))$ is self-adjoint in $\mathcal{L}^2(\mathbf{R}^n, dx)$, while from the Lévy-Khintchin formula we also deduce that it is negative definite [9]. In the quoted papers, however, the choice (49) was essentially dictated by an analogy argument and there was no real attempt to deduce it: here instead we will try to extend this idea, and to justify it within the framework of the Doob transformations.

To show the way, we here consider first the case $\phi(x) = 1$ associated to the Lebesgue measure $\mu(dx) = dx$. Every Lévy process is a time-homogeneous Markov process, and this μ acts as its invariant measure [9]. It is apparent, moreover, that here we are not required to introduce a further operator L – as we did in (43) for the Wiener case – because L_0 itself plays this role. As a consequence we can skip to prove a statement as the Theorem 6.1, for L_0 is by hypothesis the generator of a Lévy process. On the other hand, even if here μ is only σ -finite and cannot be

considered as a probability measure, we can apply the Doob transformation defined in the previous section because all the hypotheses 1-4 are met. Since L_0 is self-adjoint in $\mathcal{L}^2(\mathbf{R}^n, dx)$ (and hence for the backward generator we have $\tilde{L}_0 = L_0^\dagger = L_0$) from (33) we find

$$K = -L_0 \quad K^Y = -L_0 - i\partial_t$$

and to implement a Doob transformation – by taking the Lebesgue measure as invariant measure, $S(x) = 0$ and $E = 0$ for simplicity – we choose

$$\Psi(t, x) = \psi(x) = 1 \quad (50)$$

namely the simplest possible form of a plane wave. As a consequence in this first case we finally get

$$H = -L_0$$

namely we find the case $V(x) = 0$ of (49). Since this Hamiltonian essentially coincides with our initial generator L_0 of a Lévy process, it is straightforward to conclude – as in the Proposition 5.2 and the subsequent remarks – that to a plane wave (50) solution of a free generalized Schrödinger equation (40), namely of the free Lévy-Schrödinger equation

$$i\partial_t \Psi = H\Psi = -L_0\Psi \quad (51)$$

we can simply associate the Lévy process corresponding to L_0 . As a matter of fact this will be an improper process with generator L_0 and with the Lebesgue measure μ as initial – and invariant – measure. The free equation (51) is the case that has already been discussed at length – albeit in a more heuristic framework – in the previous papers [1]. If our Lévy process is also rotationally invariant then from (26), and within the notations of the Section 4, the Hamilton operator H becomes

$$[Hf](x) = -\frac{\alpha}{2}\nabla^2 f(x) - \int_{y \neq 0} [\delta_y^2 f](x) \ell(dy) \quad (52)$$

for any complex Schwarz function f and $x \in \mathbf{R}^n$. Note that if the jump term vanishes (namely if L_0 is the generator of a Wiener process) and $\alpha = 1$ we have

$$H = -\frac{1}{2}\nabla^2$$

i.e. the free Hamilton operator (46) of the stochastic mechanics presented in the previous section. As a consequence we see that (52) can be considered as the generalization of the usual quantum mechanical Hamiltonian by means of a jump term produced by the possible non Gaussian nature of our background Lévy process.

We turn then our attention to the more interesting case of a non constant ϕ leading to a non vanishing V in (49), and we suppose that $\alpha_{ij} = 0$ in (23), namely that L_0 is the generator of a pure jump process without an unessential Gaussian

component (we can always add it later). With this L_0 we take now a $\phi \in D(L_0)$ such that

$$\int_{\mathbf{R}^n} \phi^2(x) dx = 1, \quad \phi > 0, \text{ a.s. in } dx \quad (53)$$

and in analogy with (43) we introduce the new operator $(L, D(L))$ in $\mathcal{L}^2(\mathbf{R}^n, d\mu)$

$$Lf := \frac{L_0(\phi f) - f L_0\phi}{\phi} \quad (54)$$

with $D(L) := C_0^\infty(\mathbf{R}^n)$ and $\mu(dx) = \phi^2(x)dx$.

Proposition 7.1. *If $\phi \in D(L_0)$, then for every $f \in C_0^\infty(\mathbf{R}^n)$ we have $\phi f \in D(L_0)$ and*

$$L_0(\phi f) = f L_0\phi + \phi L_0f + \int_{y \neq 0} \delta_y \phi \delta_y f \ell(dy) \quad (55)$$

PROOF. See Appendix A. □

This statement – which generalizes an *integration by parts* rule – proves first that our definition (54) is consistent in the sense that $\phi f \in D(L_0)$; then from (54) and (55) it also gives the jump version of (44)

$$Lf = L_0f + \int_{y \neq 0} \frac{\delta_y \phi}{\phi} \delta_y f \ell(dy)$$

so that, by taking into account the equation (26) with $a = 0$, we find

$$\begin{aligned} [Lf](x) &= \int_{y \neq 0} \left(\delta_y^2 f + \frac{\delta_y \phi}{\phi} \delta_y f \right) \ell(dy) \\ &= \int_{y \neq 0} \left(\delta_y f - \frac{\phi \mathbf{1}_{B_1}(y)}{\phi + \delta_y \phi} y \cdot \nabla f \right) \frac{\phi + \delta_y \phi}{\phi} \ell(dy) \\ &= \int_{y \neq 0} [f(x+y) - f(x) - \gamma(x, y) y \cdot \nabla f(x)] \lambda(x; dy) \end{aligned} \quad (56)$$

where

$$\gamma(x, y) = \frac{\phi(x)}{\phi(x+y)} \mathbf{1}_{B_1}(y) \quad \lambda(x; dy) = \frac{\phi(x+y)}{\phi(x)} \ell(dy) \quad (57)$$

The equation (56) explicitly shows that the generator L introduced in (54) is a *Lévy-type* operator [10, 21]. We then state our main result on the existence of a (Lévy-type) Markov process associated to L and, through a subsequent Doob transformation, to the (stationary) solutions of a Lévy–Schrödinger equation.

Theorem 7.2. *The operator $(L, D(L))$ defined in (54) is closable and its closure $(\bar{L}, D(\bar{L}))$ is a self-adjoint, negative definite operator which is the infinitesimal generator of a Markov process $(X_t)_{t \in \mathbf{R}}$. The measure $\mu(dx)$ is invariant for this Markov process.*

PROOF. As in the Theorem 6.1 from $(L, D(L))$ we first define in $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ the bilinear form

$$\mathcal{E}(f, g) := -\langle Lf, g \rangle_\mu$$

with $D(\mathcal{E}) := C_0^\infty(\mathbf{R}^n)$ and we remark that from (54) we have

$$\mathcal{E}(f, g) = - \int \frac{L_0(\phi f) - f L_0 \phi}{\phi} g \phi^2 dx = - \int \phi g L_0(f \phi) dx + \int \phi g f L_0 \phi dx$$

Then from (27) with $\alpha_{ij} = 0$ we obtain

$$\begin{aligned} \mathcal{E}(f, g) &= \frac{1}{2} \iint_{y \neq 0} [\delta_y(g\phi)](x) [\delta_y(f\phi)](x) \ell(dy) dx \\ &\quad - \frac{1}{2} \iint_{y \neq 0} [\delta_y(fg\phi)](x) [\delta_y\phi](x) \ell(dy) dx \end{aligned}$$

and from (24) after some tiring but simple algebra we get

$$\mathcal{E}(f, g) = \frac{1}{2} \iint_{y \neq 0} [\delta_y f](x) [\delta_y g](x) \phi(x+y) \phi(x) \ell(dy) dx$$

This expression for \mathcal{E} has the required form (15) with vanishing killing and diffusion measures, and $J(dz, dx)$ given by $\phi(x+y)\phi(x)\ell(dy)dx$ with $z = x+y$, which is positive because of (53). Since the condition (16) is satisfied, by reproducing the same argument previously adopted in the Theorem 6.1 we get that there exists a self-adjoint, infinitesimal generator $(\bar{L}, D(\bar{L}))$ which turns out [26] to be the closure of $(L, D(L))$.

This \bar{L} generates a unique, bilateral Markov process $(X_t)_{t \in \mathbf{R}}$ on $(\mathbf{R}^n, \mathcal{B}(\mathbf{R}^n))$ having μ as its invariant measure when the conditions discussed in the remarks following the Theorem 3.8 are met. Hence, as in the Theorem 6.1, we should only check that the constant element $f_1(x) = 1$ of $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ belongs to $D(\bar{L})$ and that $\bar{L}f_1 = 0$. In fact for every $f \in C_0^\infty(\mathbf{R}^n)$ dense in $\mathcal{L}^2(\mathbf{R}^n, d\mu)$ we have again from (27) with $\alpha_{ij} = 0$ that

$$\begin{aligned} \langle f_1, \bar{L}f \rangle_\mu &= \int_{\mathbf{R}^n} [\bar{L}f] \phi^2 dx = \int_{\mathbf{R}^n} [Lf] \phi^2 dx \\ &= \int_{\mathbf{R}^n} \phi^2 \frac{L_0(\phi f) - f L_0(\phi)}{\phi} dx = \int_{\mathbf{R}^n} [\phi L_0(\phi f) - \phi f L_0(\phi)] dx \\ &= -\frac{1}{2} \iint_{y \neq 0} [\delta_y \phi \delta_y(\phi f) - \delta_y(\phi f) \delta_y \phi] dx = 0 \end{aligned}$$

Being \bar{L} self-adjoint this implies first that $f_1 \in D(\bar{L})$, and that $\langle \bar{L}f_1, f \rangle_\mu = 0$ for every $f \in C_0^\infty$ dense in $\mathcal{L}^2(\mathbf{R}^n, d\mu)$, and then that $\bar{L}f_1 = 0$. \square

This result will now put us in condition to perform a suitable Doob transformation with the confidence that we can also associate a Lévy-type, Markov process X to

the chosen wave functions. In fact, being $\mu(dx) = \rho(x)dx = \phi^2(x)dx$ an invariant measure for X_t , taking as before $S(x) = 0$ and $E \in \mathbf{R}$ namely

$$\psi(x) = \phi(x) \quad \Psi(t, x) = e^{-iEt}\phi(x)$$

and by applying (41), we immediately get the following expression for the Hamiltonian operator associated to X_t of Theorem 7.2

$$[Hf](x) := [-L_0f + Vf](x) = - \int_{y \neq 0} [\delta_y^2 f](x) \ell(dy) + V(x)f(x) \quad (58)$$

where the potential function now is

$$V(x) = \frac{[L_0\phi](x)}{\phi(x)} + E = \frac{1}{\phi(x)} \int_{y \neq 0} [\delta_y^2 \phi](x) \ell(dy) + E \quad (59)$$

showing also that Ψ is a stationary solution of

$$i\partial_t \Psi = H\Psi = (-L_0 + V)\Psi = - \int_{y \neq 0} \delta_y^2 \Psi \ell(dy) + V\Psi \quad (60)$$

namely of our Lévy-Schrödinger equation with the potential (59).

8 Cauchy noise

We will conclude the paper by proposing (in the one-dimensional case $n = 1$) two examples for the simplest stable, non Gaussian Lévy background noise produced by the generator L_0 of a Cauchy process, namely an operator of the form (26) without Gaussian term ($a = 0$) and with Lévy measure

$$\ell(dx) = \frac{dx}{\pi x^2} \quad (61)$$

Remark that in general for this Cauchy background noise with Lévy measure (61) the generator (56) becomes

$$Lf = \frac{1}{\pi} \int_{y \neq 0} \left(\frac{\delta_y^2 f}{y^2} + \frac{1}{y} \frac{\delta_y \phi}{\phi} \frac{\delta_y f}{y} \right) dy \quad (62)$$

and that the convergence of this integral in $y = 0$ is a consequence of the fact that, for $y \rightarrow 0$, $\delta_y^2 f$ vanishes at the second order, while $\delta_y \phi$ and $\delta_y f$ are infinitesimal of the first order. The corresponding pure jump Cauchy-Schrödinger equation

$$i\partial_t \Psi = - \int_{y \neq 0} \frac{\delta_y^2 \Psi}{\pi y^2} dy + V\Psi \quad (63)$$

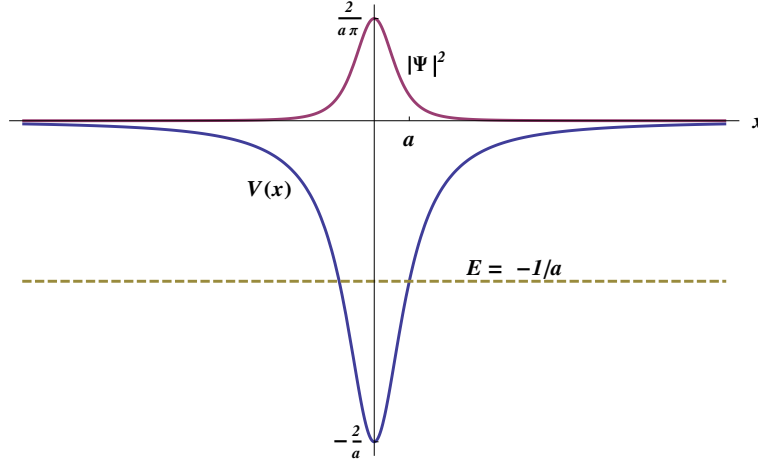


Figure 1: Potentials $V(x)$ and square modulus of the stationary wave functions $|\Psi|^2$ for the pair (65) and (66).

has already been discussed in various disguises in several previous papers [1, 6] and we will show here two examples of its stationary solutions for potentials of the form (59).

To define our invariant measure $\mu(dx) = \rho(x)dx = \phi^2(x)dx$ let us take first of all the functions

$$\phi(x) = \sqrt{\frac{2a}{\pi}} \frac{a}{a^2 + x^2} \quad \rho(x) = \phi^2(x) = \frac{2}{a\pi} \left(\frac{a^2}{a^2 + x^2} \right)^2 \quad (64)$$

so that the stationary *pdf* will be that of a $\mathfrak{T}_a(3)$ Student law [1]. A direct calculation of (59) with these entries will then show that, by choosing the energy origin so that $E = -1/a$ and $V(\pm\infty) = 0$, we have

$$V(x) = -\frac{2a}{x^2 + a^2} \quad (65)$$

In other words the wave function

$$\Psi(x, t) = \sqrt{\frac{2a}{\pi}} \frac{a}{a^2 + x^2} e^{-it/a} \quad (66)$$

turns out to be a stationary solution of the equation (63) with potential (65) corresponding to the eigenvalue $E = -1/a$. This result is summarized in the Figure 1. On the other hand we see from the Theorem 7.2 that to the wave function (66) we can also associate a Lévy-type, Markov process X_t completely defined by the generator (56) with

$$\gamma(x, y) = \frac{a^2 + (x + y)^2}{a^2 + x^2} \mathbf{1}_{[-1,1]}(y) \quad \lambda(x; dy) = \frac{a^2 + x^2}{a^2 + (x + y)^2} \frac{dy}{\pi y^2}$$

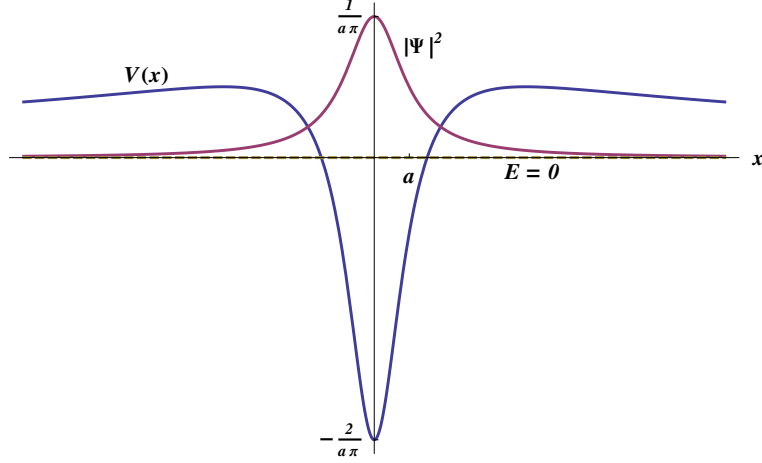


Figure 2: Potentials $V(x)$ and square modulus of the stationary wave functions $|\Psi|^2$ for the pair (67) and (68).

as can be deduced from (57) and (64).

In a similar vein, and always for the same equation (63), we can take as a second example the starting functions

$$\phi(x) = \sqrt{\frac{a}{\pi}} \frac{1}{\sqrt{a^2 + x^2}} \quad \rho(x) = \phi^2(x) = \frac{1}{\pi} \frac{a}{a^2 + x^2}$$

namely the *pdf* of a $\mathfrak{C}(a) = \mathfrak{T}_a(1)$ Cauchy law. Treading the same path as before, a slightly more laborious calculation will show that, by choosing now $E = 0$ to have again $V(\pm\infty) = 0$, we find

$$V(x) = -\frac{2}{\pi} \left[\frac{1}{\sqrt{a^2 + x^2}} + \frac{x}{a^2 + x^2} \log \left(\sqrt{1 + \frac{x^2}{a^2}} - \frac{x}{a} \right) \right] \quad (67)$$

so that now the wave function

$$\Psi(x, t) = \sqrt{\frac{a}{\pi}} \frac{1}{\sqrt{a^2 + x^2}} \quad (68)$$

is stationary solution with eigenvalue $E = 0$ of the equation (63) with potential (67). The potential and the corresponding *pdf* are depicted in the Figure 2. The Lévy-type, Markov process X_t associated to this wave function is again defined by the generator (56) with

$$\gamma(x, y) = \sqrt{\frac{a^2 + (x+y)^2}{a^2 + x^2}} \mathbf{1}_{[-1,1]}(y) \quad \lambda(x; dy) = \sqrt{\frac{a^2 + x^2}{a^2 + (x+y)^2}} \frac{dy}{\pi y^2}$$

The two generators introduced here completely determine the two Markov processes associated to our stationary solutions of the Cauchy-Schrödinger equation (63).

9 Conclusions

The adoption, proposed in a few previous papers [1], of the L - S equation – a generalization of the usual Schrödinger equation associated to the Wiener process – amounts in fact to suppose that the behavior of the physical systems in consideration is based on an underlying Lévy process that can have both Gaussian (continuous) and non Gaussian (jumping) components. The consequent use of all the gamut of the *id*, even non stable, processes on the other hand turns out to be important and physically meaningful because there are significant cases that fall in the domain of the L - S picture, without being in that of a stable (fractional) Schrödinger equation [7]. In particular the simplest form of a relativistic, free Schrödinger equation [1, 6, 16] can be associated with a peculiar type of self-decomposable, non stable process acting as background noise. Moreover in many instances of the L - S equation the resulting energy-momentum relations can be seen as small corrections to the classical relations for small values of certain parameters [1]. It must also be remembered that – in discordance with the stable, fractional case – our models are not tied to the use of background noises with infinite variances: these can indeed be finite even for purely non Gaussian noises – as for instance in the case of the relativistic, free Schrödinger equation – and can then be used as a legitimate measure of the dispersion. Finally let us recall that a typical non stable, Student Lévy noise seems to be suitable for applications, as for instance in the models of halo formation in intense beam of charged particles in accelerators [8, 12, 30].

In view of all that it was then important to explicitly give more rigorous details about the formal association between L - S wave functions and the underlying Lévy processes, namely a true generalized stochastic mechanics. And it was urgent also to explore this Lévy–Nelson stochastic mechanics by adding suitable potentials to the free L - S equation, and by studying the corresponding possible stationary and coherent states. To this end we found expedient to broaden the scope of our enquiry to the field of Markov processes more general than the Lévy processes

From this standpoint in the present paper we have studied – with the aid of the Dirichlet forms – under what conditions the generalized Schrödinger equation (40), with a fairly general self-adjoint Hamiltonian H , admits a stochastic representation in terms of Markov processes: a conspicuous extension of the well known, older results of the stochastic mechanics [2]. More precisely it has been shown how we can associate to every stationary wave functions Ψ , of the form (35) and solutions of the equation (40), a bilateral, time-homogeneous Markov process $(X_t)_{t \in \mathbf{R}}$ whose generator L in its turn plays the role of the starting point to produce exactly the Hamiltonian H of the equation (40). This association moreover is defined in such a way that, in analogy with the well known Born postulate of quantum mechanics, $|\Psi|^2$ always coincides with the *pdf* of $(X_t)_{t \in \mathbf{R}}$.

The whole procedure adopted here is inherently based on the Doob transformation (36) previously adopted [19, 20] in the particular case of the Wiener process to get the usual Schrödinger equation, as we have summarized in the Section 6. This

choice allows us, among other things, to sidestep for the time being the problem of the explicit definition of a dynamics for jump processes that would pave the way to recover our association along a more traditional path, either by means of the Newton law, as originally done [2], or through a variational approach, as in later advances [5]. The definition of these structures, whose preliminary results have already been presented elsewhere [22], seems indeed at present to require more ironing and will be the object of future enquiries.

We have then focused our attention on the case of the L - S equation (60), a particular kind of generalized Schrödinger equation characterized by an Hamiltonian (58) derived from a Lévy process generator. This equation was previously suggested only in an heuristic way [1], while in the present paper we succeeded in proving a few rigorous results: first we showed how the stationary wave functions of this L - S equation actually satisfy the conditions required to be associated to Markov processes; then we pointed out that the L - S Hamiltonian H is composed of a kinetic part (the generator L_0 of our background, symmetric Lévy process) plus a potential V , a term that was lacking of a justification in our previous formulations. Third we also proved that the bilateral, time-homogeneous Markov processes associated to a stationary wave function Ψ turn out in fact to be Lévy-type processes, a generalization of the Lévy processes which is at present under intense scrutiny [21]. Finally we presented a few examples of stationary solutions of L - S equations with Cauchy background noise.

These were much needed advances conspicuously absent in the previous papers, as already explicitly remarked there, It would be important now first to extend these results even to the non stationary wave packets solutions of the generalized Schrödinger equation (40), at least in its L - S form (60), that have been extensively studied in a recent paper [1] where their inherent multi-modality has been put in evidence. Then to give a satisfactory formulation of the Nelson dynamics of the jump processes involved: a much needed advance that would constitute an open window on the true nature of these special processes. And finally a detailed study of the characteristics of the Lévy-type processes associated to the L - S wave functions: this too will be the subject of future papers.

A Proof of Proposition 7.1

We begin by proving (55) for $\phi \in C_0^\infty(\mathbf{R}^n) \subseteq \mathcal{S}(\mathbf{R}^n) \subseteq D(L_0)$. In fact in this case we apparently have $\phi f \in C_0^\infty(\mathbf{R}^n)$, while from (23) and (25) with $A = 0$ it is

$$\begin{aligned}
 L_0(\phi f) &= \int_{y \neq 0} \delta_y^2(\phi f) \ell(dy) \\
 &= f \int_{y \neq 0} \delta_y^2 \phi \ell(dy) + \phi \int_{y \neq 0} \delta_y^2 f \ell(dy) + \int_{y \neq 0} \delta_y \phi \delta_y f \ell(dy) \\
 &= f L_0 \phi + \phi L_0 f + \int_{y \neq 0} \delta_y \phi \delta_y f \ell(dy)
 \end{aligned} \tag{69}$$

because we can see that the third term of (69) belongs to $\mathcal{L}_{\mathbf{R}}^2(\mathbf{R}^n, dx)$. Being indeed f and ϕ bounded, and $\phi \in C_0^\infty(\mathbf{R}^n) \subseteq D(L_0) \subseteq D(\mathcal{E}_0)$, from (28) we get

$$\begin{aligned} \int \left| \int_{y \neq 0} \delta_y f \delta_y \phi \ell(dy) \right|^2 dx &\leq \int \int_{y \neq 0} |\delta_y f \delta_y \phi|^2 \ell(dy) dx \\ &\leq 4\kappa^2 \int \int_{y \neq 0} |\delta_y \phi|^2 \ell(dy) dx < \infty \end{aligned}$$

with $\kappa = \sup |f|$.

If instead we suppose that $\phi \in D(L_0) \subseteq D(\mathcal{E}_0)$, we have $\phi f \in \mathcal{L}_{\mathbf{R}}^2(\mathbf{R}^n, dx)$ since f is bounded. As a first step let us show that $\phi f \in D(\mathcal{E}_0) \supseteq D(L_0)$: because of (28) to do that we have just to prove that

$$\int \int_{y \neq 0} |\delta_y(\phi f)|^2 \ell(dy) dx < \infty \quad (70)$$

Remark that from (24) we have

$$\begin{aligned} \int \int_{y \neq 0} |\delta_y(\phi f)|^2 \ell(dy) dx &\leq 2 \left[\int \int_{y \neq 0} |\phi \delta_y f|^2 \ell(dy) dx + \int \int_{y \neq 0} |f \delta_y \phi|^2 \ell(dy) dx \right. \\ &\quad \left. + \int \int_{y \neq 0} |\delta_y \phi \delta_y f|^2 \ell(dy) dx \right] \quad (71) \end{aligned}$$

The second and the third integrals on the right of (71) are finite because f is bounded and $\phi \in D(\mathcal{E}_0)$; as for the first integral, instead, since $\phi \in \mathcal{L}_{\mathbf{R}}^2(\mathbf{R}^n, dx)$, it is enough to remark that, from the property (18) of Lévy measure and since $f \in C_0^\infty(\mathbf{R}^n)$, we have

$$\begin{aligned} \int_{y \neq 0} |\delta_y f|^2(x) \ell(dy) &= \int_{|y| \leq 1, y \neq 0} |\delta_y f|^2(x) \ell(dy) + \int_{|y| \geq 1} |\delta_y f|^2(x) \ell(dy) \\ &\leq C \int_{|y| \leq 1, y \neq 0} |y|^2 |\nabla f(x)|^2 \ell(dy) + C' \int_{|y| \geq 1} \ell(dy) \\ &\leq C'' \int_{|y| \leq 1, y \neq 0} |y|^2 \ell(dy) + C' \int_{|y| \geq 1} \ell(dy) = M < \infty \end{aligned}$$

with $C'' = C \sup |\nabla f(x)|^2$. In a similar way we can prove that also $[L_0 f](x)$ is bounded, a remark that will be useful in the following.

In order to complete the proof of the proposition we will show now that it exists a $\psi \in \mathcal{L}_{\mathbf{R}}^2(\mathbf{R}^n, dx)$ with the form of the second member of (55), and such that for every $g \in D(L_0)$

$$\langle L_0 g, \phi f \rangle = \langle g, \psi \rangle$$

If this is true we can indeed deduce from the self-adjointness of L_0 that $f\phi \in D(L_0)$, and that (55) is verified. On the other hand, since the Proposition 3.9 actually states

that $C_0^\infty(\mathbf{R}^n)$ is a *core* for $(L_0, D(L_0))$, we can restrict our discussion to $g \in C_0^\infty(\mathbf{R}^n)$, so that we have

$$\begin{aligned} \langle L_0 g, \phi f \rangle &= \langle f L_0 g, \phi \rangle \\ &= \langle L_0(fg), \phi \rangle - \langle g L_0 f, \phi \rangle - \int \phi \left(\int_{y \neq 0} \delta_y g \delta_y f \ell(dy) \right) dx \\ &= \langle g, f L_0 \phi \rangle - \langle g, \phi L_0 f \rangle - \int \int_{y \neq 0} \phi \delta_y g \delta_y f \ell(dy) dx \end{aligned} \quad (72)$$

where the second equality follows from the fact that (55) has been already proved for $f, g \in C_0^\infty(\mathbf{R}^n)$, while the third equality comes from the previously quoted $L_0 f$ boundedness (so that $\phi L_0 f \in \mathcal{L}_R^2(\mathbf{R}^n, dx)$ and the scalar products exist) and the L_0 self-adjointness. Take now the third term of (72): according to (24) we have

$$\phi \delta_y g \delta_y f = \delta_y(\phi g) \delta_y f - g \delta_y \phi \delta_y f - \delta_y \phi \delta_y f \delta_y g \quad (73)$$

Since we have seen that $\phi g \in D(\mathcal{E}_0)$, from (27) we first find

$$\int \int_{y \neq 0} \delta_y(\phi g) \delta_y f \ell(dy) dx = -2\mathcal{E}_0(\phi g, f) = -2\langle \phi g, L_0 f \rangle = -2\langle g, \phi L_0 f \rangle \quad (74)$$

Then, taking now into account that

$$\int \int_{y \neq 0} |\delta_y \phi \delta_y f \delta_y g|^2 \ell(dy) dx \leq C \int \int_{y \neq 0} |\delta_y \phi|^2 \ell(dy) dx < \infty$$

from the Fubini's theorem and the symmetry of $\ell(dy)$ it results with the change of variables $x \rightarrow x + y$ and $y \rightarrow -y$ that

$$\int \int_{y \neq 0} \delta_y \phi \delta_y f \delta_y g \ell(dy) dx = - \int \int_{y \neq 0} \delta_y \phi \delta_y f \delta_y g \ell(dy) dx = 0 \quad (75)$$

Finally, by observing that since f is bounded and $\phi \in D(\mathcal{E}_0)$ the scalar products in (75) are correctly defined, we have

$$\int_{y \neq 0} [\delta_y \phi](x) [\delta_y f](x) \ell(dy) \in \mathcal{L}_R^2(\mathbf{R}^n, dx)$$

by collecting (72), (73), (74) and (75) we get

$$\langle L_0 g, \phi f \rangle = \left\langle g, f L_0 \phi + \phi L_0 f + \int_{y \neq 0} \delta_y \phi \delta_y f \ell(dy) \right\rangle$$

which completes the proof.

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