CONDITIONED RANDOM WALKS
FROM KAC-MOODY ROOT SYSTEMS

CÉDRIC LECOUVEY, EMMANUEL LESIGNE, AND MARC PEIGNÉ

Abstract. Random paths are time continuous interpolations of random walks. By using the Littelmann path model, we associate to each irreducible highest weight module of a Kac Moody algebra $g$ a random path $W$. Under suitable hypotheses, we make explicit the probability of the event $E$: “$W$ never exits the Weyl chamber of $g$.” We then give the law of the random walk defined by $W$ conditioned by the event $E$ and prove this law can be recovered by applying to $W$ a path transform of Pitman type. This generalizes the main results of Neil O'Connell (2003) and the authors (2012) to Kac Moody root systems and arbitrary highest weight modules. Our approach here is new and more algebraic than in the aforementioned works. We indeed fully exploit the symmetry of our construction under the action of the Weyl group of $g$ which permits us to avoid delicate generalizations of our previous results on renewal theory.

1. Introduction

The purpose of the paper is to study conditionings of random walks using algebraic and combinatorial tools coming from representation theory of Lie algebras and their infinite-dimensional generalizations (Kac-Moody algebras). We extend in particular some results previously obtained in [15], [16], [1], [10] and [11] to random paths in the weight lattice of any Kac-Moody algebra $g$. To do this, we consider a fixed $g$-module $V$ in the category $O_{int}$ (a convenient generalization of the category of the finite-dimensional representations of Lie algebras). It decomposes as the direct sum of its weight spaces, each such space being parametrized by a vector of the weight lattice of $g$. The transitions of the random walk associated to $V$ are then the weights of $V$.

The prototype of the results we obtain appears in the seminal paper [15] by O’Connell, where it is shown that the law of the one-way simple random walk $W$ in $\mathbb{Z}^n$ conditioned to stay in the cone $C = \{(x_1, \ldots, x_n) \in \mathbb{Z}^n \mid x_1 \geq \cdots \geq x_n \geq 0\}$ and with drift in the interior $\bar{C}$ of $C$ is the same as the law of a Markov chain $H$ obtained by applying to $W$ a generalization of the Pitman transform. This transform is defined via an insertion procedure on semistandard tableaux classically used in representation theory of $\mathfrak{sl}_n(\mathbb{C})$. The transition matrix of $H$ can then be expressed in terms of the Weyl characters (Schur functions) of the irreducible $\mathfrak{sl}_n(\mathbb{C})$-modules. Here the transitions of the random walk $W$ are the vectors of the standard basis of $\mathbb{Z}^n$ which correspond to the weights of the defining representation $\mathbb{C}^n$ of $\mathfrak{sl}_n(\mathbb{C})$. In addition to the insertion procedure on tableaux and some classical
facts about representation theory of $\mathfrak{sl}_n(\mathbb{C})$, the main ingredients of O’Connell’s result are a theorem of Doob on Martin boundary together with the asymptotic behavior of tensor product multiplicities associated to the decompositions of $V^\otimes \ell$ in its irreducible components (which in this case are counted by standard skew tableaux).

We consider in \cite{10} more general random walks $W$ with transitions the weights of a finite-dimensional irreducible $\mathfrak{g}$-module $V$ where $\mathfrak{g}$ is a Lie algebra. The law of $W$ is constructed so that the probabilities of the paths depend only on their lengths and their ends. We then show that the process $H$ obtained by applying to $W$ a generalization of the Pitman transform introduced in \cite{1} is a Markov chain. When $V$ is a minuscule representation (i.e. when the weights of $V$ belong to the same orbit under the action of the Weyl group of $\mathfrak{g}$) and $W$ has drift in the interior $\mathcal{C}$ of the cone $\mathcal{C}$ of dominant weights, we prove that $H$ has the same law as $W$ conditioned to never exit $\mathcal{C}$. Similarly to the result of O’Connell, this common law can be expressed in terms of the Weyl characters of the simple $\mathfrak{g}$-modules. Nevertheless the methods differ from \cite{15} notably because there was no previously known asymptotic behavior for the relevant tensor multiplicities in the more general cases we study. In fact, we proceed by establishing a quotient renewal theorem for general random walks conditioned to stay in a cone. When $W$ is not defined from a minuscule representation, we also show that the law of $W$ conditioned to never exit $\mathcal{C}$ cannot coincide with that of $H$.

In \cite{11}, we use the renewal theorem of \cite{10} and insertion procedures on tableaux appearing in the representation theory of the Lie superalgebras $\mathfrak{gl}(m,n)$ and $\mathfrak{q}(n)$ to extend the results of \cite{15} to one-way simple random walks conditioned to never exit cones $\mathcal{C}'$ for examples of cones $\mathcal{C}'$ different from $\mathcal{C}$.

In view of the results of \cite{10}, it is natural to ask whether the Markov chain $H$ is related to a suitable conditioning of $W$ in the nonminuscule case. Also what can be said about the law of $W$ conditioned to never exit $\mathcal{C}'$? In the sequel, we will answer both questions (partially for the second) not only for random walks defined from representations of Lie algebras but, more generally, for similar random walks with transitions the weights of a highest weight module $V(\kappa)$ associated to a Kac-Moody algebra $\mathfrak{g}$ of rank $n$.

By using the Littelmann path model \cite{13}, one can associate to $V(\kappa)$ a countable set of piecewise continuous linear paths $B(\pi_{\kappa})$ in the weight lattice $P \subset \mathbb{R}^n$ of $\mathfrak{g}$. These paths (called elementary in the sequel) are regarded as functions $\pi : [0,1] \to \mathbb{R}^n$ such that $\pi(0) = 0$ and $\pi(1) \in P$. The weights of $V(\kappa)$ are then the elements $\pi(1), \pi \in B(\pi_{\kappa})$. The set $B(\pi_{\kappa})$ has the structure of a colored and oriented graph isomorphic to the crystal graph of $V(\kappa)$ as defined by Kashiwara.

We use the crystal graph structure on $B(\pi_{\kappa})$ to endow it as in \cite{10} with a probability density $p$. This yields a random variable $X$ defined on $B(\pi_{\kappa})$ with probability distribution $p$. Let $(X_\ell)_{\ell \geq 1}$ be a sequence of i.i.d. random variables with the same law as $X$. We then define a continuous random path $W$ such that for any $t \geq 0$, $W(t) = X_1(1) + \cdots + X_{\ell-1}(1) + X_\ell(\ell - t)$ for any $t \in [\ell - 1, \ell]$. The sequence $W = (W_\ell)_{\ell \geq 0}$ defined by $W_\ell = W(\ell)$ is then a random walk with transitions the weights of $V(\kappa)$ as considered in \cite{10}. The main result of the paper is that, when $W$ has drift in $\mathcal{C}$ (i.e. in the interior of the Weyl chamber of $\mathfrak{g}$), the law of its conditioning by the event $E = (W(t) \in \mathcal{C}$ for any $t \geq 0)$ can be simply expressed in terms of the Weyl-Kac characters. So the results of \cite{10} remain
true for a conditioning holding on the whole continuous trajectory (not only on its
discrete version at integer time). We also prove that the conditioned law so obtained
coincides with the law of the image of $W$ by the generalized Pitman transform.
When $g$ is finite-dimensional and $\kappa$ is minuscule we recover in particular the main
results of [15] and [10]. On the representation theory side, our results also lead to
asymptotic behavior of tensor product multiplicities of Kac-Moody highest weight
modules.

Nevertheless our approach differs from that of [10] since we do not use any
renewal theorem. Our strategy is more algebraic: we exploit the symmetry of the
modules.

2.1. Background on Markov chains. Consider a probability space $(\Omega, F, P)$ and
a countable set $M$. A sequence $Y = (Y_\ell)_{\ell \geq 0}$ of random variables defined on $\Omega$ with
values in $M$ is a Markov chain when
\[
P(Y_{\ell+1} = \mu_{\ell+1} \mid Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0) = P(Y_{\ell+1} = \mu_{\ell+1} \mid Y_\ell = \mu_\ell)
\]
for any $\ell \geq 0$ and any $\mu_0, \ldots, \mu_\ell, \mu_{\ell+1} \in M$. The Markov chains considered in
the sequel will also be assumed time homogeneous, that is, $P(Y_{\ell+1} = \lambda \mid Y_\ell = \mu) =
\Pr(Y_{\ell+1} = \lambda \mid Y_\ell = \mu)$ for any $\ell \geq 1$ and $\mu, \lambda \in M$. For all $\mu, \lambda$ in $M$, the transition
probability from $\mu$ to $\lambda$ is then defined by
\[
\Pi(\mu, \lambda) = \Pr(Y_{\ell+1} = \lambda \mid Y_\ell = \mu),
\]
and we refer to $\Pi$ as the transition matrix of the Markov chain $Y$. The distribution
of $Y_0$ is called the initial distribution of the chain $Y$.

In the following, we will assume that $M$ is a subset of the euclidean space $\mathbb{R}^n$
for some $n \geq 1$ and that the initial distribution of the Markov chain $Y = (Y_\ell)_{\ell \geq 0}$
has full support, i.e. $\Pr(Y_0 = \lambda) > 0$ for any $\lambda \in M$. In [10], we considered a
nonempty set $C \subset M$ and an event $E \in \mathcal{T}$ such that $\Pr(E \mid Y_0 = \lambda) > 0$ for all $\lambda \in C$
and $\Pr(E \mid Y_0 = \lambda) = 0$ for all $\lambda \notin C$; this implied that $\Pr(E) > 0$, and we could
thus define the conditional probability $Q$ relative to this event: $Q(\cdot) := \Pr(\cdot \mid E)$. For
example, we considered the event $E := (Y_\ell \in C$ for any $\ell \geq 0)$. In the present work
we will study more general situations, which involves introducing some generalities about continuous time Markov processes.

A continuous time Markov process \( Y = (Y(t))_{t \geq 0} \) on \((\Omega, \mathcal{F}, \mathbb{P})\) with values in \(\mathbb{R}^n\) is a measurable family of random variables defined on \((\Omega, \mathcal{F}, \mathbb{P})\) such that, for any integer \(k \geq 1\) and any \(0 \leq t_1 < \cdots < t_k\) the conditional distribution of \(Y(t_{k+1})\) given \(Y(t_1), \ldots, Y(t_k)\) is equal to the conditional distribution of \(Y(t_{k+1})\) given \(Y(t_k)\); in other words, for almost all \((y_1, \ldots, y_k)\) with respect to the distribution of the random vector \((Y(t_1), \ldots, Y(t_k))\) and for all Borel sets \(B \subset \mathbb{R}^n\)

\[
\mathbb{P}(Y(t_{k+1}) \in B \mid Y(t_1) = y_1, \ldots, Y(t_k) = y_k) = \mathbb{P}(Y(t_{k+1}) \in B \mid Y(t_k) = y_k).
\]

From now on, we consider an \(\mathbb{R}^n\)-valued Markov process \((Y(t))_{t \geq 0}\) defined on \((\Omega, \mathcal{F}, \mathbb{P})\) and we assume the following conditions:

(i) \(M \subset \mathbb{R}^n\).

(ii) For any integer \(\ell \geq 0\)

\[
Y_\ell := Y(\ell) \in M \quad \mathbb{P}\text{-almost surely.}
\]

It readily follows that the sequence \(Y = (Y_t)_{t \geq 0}\) is an \(M\)-valued Markov chain.

(iii) For any integer \(\ell \geq 0\), the conditional distribution of \((Y(t))_{t \geq \ell}\) given \(Y_\ell\) is equal to the one of \((Y(t))_{t \geq 0}\) given \(Y_0\); in other words, for any Borel set \(B \subset (\mathbb{R}^n)^{\mathbb{N}_{\leq 0} + \infty}\) and any \(\lambda \in M\), one gets

\[
\mathbb{P}((Y(t))_{t \geq 0} \mid Y_\ell = \lambda) = \mathbb{P}((Y(t))_{t \geq 0} \mid Y_0 = \lambda).
\]

In the following, we will assume that the initial distribution of the Markov process \((Y(t))_{t \geq 0}\) has full support, i.e. \(\mathbb{P}(Y(0) = \lambda) > 0\) for any \(\lambda \in M\). We will also consider a nonempty set \(C \subset \mathbb{R}^n\) and will assume that the probability of the event \(E := (Y(t) \in C\) for any \(t \geq 0\)\) is positive; the conditional probability \(Q\) relative to \(E\) is thus well defined. The following proposition can be deduced from our hypotheses and the Markov property of \(Y\). We postpone its proof to the appendix.

Proposition 2.1. Let \((Y(t))_{t \geq 0}\) be a continuous time Markov process with values in \(\mathbb{R}^n\) satisfying conditions (1) and (2) and \(C \subset \mathbb{R}^n\) such that the event \(E := (Y(t) \in C\) for any \(t \geq 0\)\) has positive probability measure. Then, under the probability \(Q(\cdot) = \mathbb{P}(\cdot | E)\), the sequence \((Y_\ell)_{\ell \geq 0}\) is still a Markov chain with values in \(C \cap M\) and transition probabilities given by

\[
\forall \mu, \lambda \in C \cap M \quad Q(Y_{\ell+1} = \lambda \mid Y_\ell = \mu) = \frac{\Pi^E(\mu, \lambda) \mathbb{P}(E \mid Y_0 = \lambda)}{\mathbb{P}(E \mid Y_0 = \mu)}
\]

where \(\Pi^E(\mu, \lambda) = \mathbb{P}(Y_{\ell+1} = \lambda, Y(t) \in C \text{ for } t \in [\ell, \ell + 1] \mid Y_\ell = \mu)\). We will denote by \(\Pi^E\) this Markov chain.

To simplify the notation we will denote by \(C\) the set \(C \cap M\) as soon as we consider the Markov chain \((Y_\ell)_{\ell \geq 0}\) and \(\Pi^E = (\Pi(\mu, \lambda))_{\mu, \lambda \in C}\) the “restriction” of the transition matrix \(\Pi\) to the event \(E\) where

\[
\Pi^E(\mu, \lambda) = \mathbb{P}(Y_{\ell+1} = \lambda, Y(t) \in C \text{ for } t \in [\ell, \ell + 1] \mid Y_\ell = \mu).
\]

So \(\Pi^E(\mu, \lambda)\) gives the probability of the transition from \(\mu\) to \(\lambda\) when \(Y(t)\) remains in \(C\) for \(t \in [\ell, \ell + 1]\).

A substochastic matrix on the countable set \(M\) is a map \(T : M \times M \to [0, 1]\) such that \(\sum_{y \in M} T(x, y) \leq 1\) for any \(x \in M\). If \(\Pi, \Pi'\) are substochastic matrices on \(M\),
we define their product $\Pi \times \Pi'$ as the substochastic matrix given by the ordinary product of matrices:

$$\Pi \times \Pi'(x, y) = \sum_{z \in M} \Pi(x, z)\Pi'(z, y).$$

A function $h : M \to \mathbb{R}$ is harmonic for the substochastic transition matrix $\Pi$ when we have $\sum_{y \in M} \Pi(x, y)h(y) = h(x)$ for any $x \in M$. Consider a (strictly) positive harmonic function $h$. We can then define the Doob transform of $\Pi$ by $h$ (also called the $h$-transform of $\Pi$) setting

$$\Pi_h(x, y) = \frac{h(y)}{h(x)}\Pi(x, y).$$

We then have $\sum_{y \in M} \Pi_h(x, y) = 1$ for any $x \in M$. Thus $\Pi_h$ is stochastic and can be interpreted as the transition matrix for a certain Markov chain.

An example is given in formula (3): the state space is now $C$ and the harmonic function is $h_E(\mu) := P(E \mid Y_0 = \mu)$; the transition matrix $\Pi_E^{\circ}$ is the transition matrix of the Markov chain $Y^E$.

### 2.2. Elementary random paths.

Consider a $\mathbb{Z}$-lattice $P$ with finite rank $d$. Set $P_\mathbb{R} = P \otimes_2 \mathbb{R}$ so that $P$ can be regarded as a $\mathbb{Z}$-lattice of rank $d$ in $\mathbb{R}^d$. An elementary path is a piecewise continuous linear map $\pi : [0, 1] \to P_\mathbb{R}$ such that $\pi(0) = 0$ and $\pi(1) \in P$. Two paths $\pi_1$ and $\pi_2$ are considered as identical if there exists a piecewise, surjective continuous and nondecreasing map $u : [0, 1] \to [0, 1]$ such that $\pi_2 = \pi_1 \circ u$. Let $\|\cdot\|$ be any choice of norm on $\mathbb{R}^d$.

The set $\mathcal{F}$ of continuous functions from $[0, 1]$ to $P_\mathbb{R}$ is equipped with the norm of uniform convergence we also denote by $\|\cdot\|$. This means that for any $\pi \in \mathcal{F}$, one has $\|\pi\|_\infty := \sup_{t \in [0, 1]} \|\pi(t)\|$. Let $B$ be a countable set of paths and fix a probability distribution $p = (p_\pi)_{\pi \in B}$ on $B$ such that $p_\pi > 0$ for any $\pi \in B$. Let $X$ be a random variable defined on a probability space $(\Omega, \mathcal{F}, \mathbb{P})$ and with distribution $p$ (in other words $\mathbb{P}(X = \pi) = p_\pi$ for any $\pi \in B$). The variable $X$ admits a moment of order 1 (namely $\mathbb{E}(\|X\|_\infty) < +\infty$) when the series of functions $\sum_\pi p_\pi \|\pi\|_\infty$ converges on $[0, 1]$. We then set

$$m := \mathbb{E}(X) = \sum_{\pi \in B} p_\pi \pi.$$

The concatenation $\pi_1 \ast \pi_2$ of two elementary paths $\pi_1$ and $\pi_2$ is defined by

$$\pi_1 \ast \pi_2(t) = \begin{cases} \pi_1(2t) & \text{for } t \in [0, \frac{1}{2}], \\ \pi_1(1) + \pi_2(2t - 1) & \text{for } t \in \left[\frac{1}{2}, 1\right]. \end{cases}$$

In the sequel, $C$ is a closed convex cone in $P_\mathbb{R}$ with interior $\hat{C}$, and we set $P_+ = C \cap P$.

### 2.3. Random paths.

Let $B$ be a set of elementary paths and $(X_\ell)_{\ell \geq 1}$ a sequence of i.i.d. random variables with law $X$ where $X$ is the random variable with values in $B$ introduced in subsection 2.2. We define the random process $W$ as follows: for any $\ell \in \mathbb{Z}_{>0}$ and $t \in [\ell, \ell + 1]$,

$$W(t) := X_1(1) + X_2(1) + \cdots + X_{\ell-1}(1) + X_\ell(t-\ell).$$

The sequence of random variables $W = (W_\ell)_{\ell \geq 1} := (W(\ell))_{\ell \geq 1}$ is a random walk with set of increments $I := \{\pi(1) \mid \pi \in B\}$. 
For any \( \ell \geq 1 \), let \( \psi_\ell \) be the map defined by
\[
\forall \mu \in \mathcal{C} \quad \psi_\ell(\mu) = \mathbb{P}_\mu(W(t) \in \mathcal{C} \text{ for any } t \in [0, \ell])
\]
so that \( \psi_\ell(\mu) \) is the probability that \( W \) starting at \( \mu \) remains in \( \mathcal{C} \) for any \( t \in [0, \ell] \). As \( \ell \to +\infty \), the sequence of functions \( (\psi_\ell)_{\ell \geq 0} \) converges to the function \( \psi \) defined by
\[
\forall \mu \in \mathcal{C} \quad \psi(\mu) = \mathbb{P}_\mu(W(t) \in \mathcal{C} \text{ for any } t \geq 0).
\]

**Proposition 2.2.** Assume \( \mathbb{E}(\|X\|_\infty) < +\infty \) and \( m(1) \notin \hat{C} \). Then for any \( \mu \in \mathcal{C} \), we have \( \psi(\mu) = 0 \).

**Proof.** Observe that \( \psi(\mu) = \mathbb{P}_\mu(W(t) \in \mathcal{C} \text{ for any } t \geq 0) \leq \mathbb{P}_\mu(W_\ell \in \mathcal{C} \text{ for any } \ell \geq 0) \). By a straightforward application of the strong law of large numbers for the random walk \( W \) (see [10] for more details), we have \( \mathbb{P}_\mu(W_\ell \in \mathcal{C} \text{ for any } \ell \geq 0) = 0 \) when \( m(1) \notin \hat{C} \). Thus \( \psi(\mu) = 0 \) when \( m(1) \notin \hat{C} \). \( \square \)

**Remark.** The hypothesis \( \mathbb{E}(\|X\|_\infty) < +\infty \) suffices in fact to prove also that \( \psi(\mu) > 0 \) when \( m(1) \in \hat{C} \) and there exists at least \( \pi \in \mathcal{B} \) such that \( \text{Im } \pi \subseteq \mathcal{C} \). In the context of this paper, this will readily follow from Theorem 6.2 so we do not pursue this direction.

### 3. Representations of symmetrizable Kac-Moody algebras

#### 3.1. Symmetrizable Kac-Moody algebras

Let \( A = (a_{i,j}) \) be an \( n \times n \) generalized Cartan matrix of rank \( r \). This means that the entries \( a_{i,j} \in \mathbb{Z} \) satisfy the following conditions:

1. \( a_{i,j} \in \mathbb{Z} \) for \( i, j \in \{1, \ldots, n\} \),
2. \( a_{i,i} = 2 \) for \( i \in \{1, \ldots, n\} \),
3. \( a_{i,j} = 0 \) if and only if \( a_{j,i} = 0 \) for \( i, j \in \{1, \ldots, n\} \).

We will also assume that \( A \) is indecomposable: given subsets \( I \) and \( J \) of \( \{1, \ldots, n\} \), there exists \( (i, j) \in I \times J \) such that \( a_{i,j} \neq 0 \). We refer to [3] for the classification of indecomposable generalized Cartan matrices. Recall there exist only three kinds of such matrices: when all the principal minors of \( A \) are positive, \( A \) is of finite type and corresponds to the Cartan matrix of a simple Lie algebra over \( \mathbb{C} \); when all the proper principal minors of \( A \) are positive and \( \det(A) = 0 \) the matrix \( A \) is said to be of affine type; otherwise \( A \) is of indefinite type. For technical reasons, from now on we will restrict ourselves to symmetrizable generalized Cartan matrices; i.e. we will assume there exists a diagonal matrix \( D \) with entries in \( \mathbb{Z}_{>0} \) such that \( DA \) is symmetric.

The root and weight lattices associated to a generalized symmetrizable Cartan matrix are defined by mimicking the construction of the Lie algebras. Let \( P^\vee \) be a free abelian group of rank \( 2n - r \) with \( \mathbb{Z} \)-basis \( \{h_1, \ldots, h_n\} \cup \{d_1, \ldots, d_{n-r}\} \). Set \( \mathfrak{h} := P^\vee \otimes \mathbb{C} \) and \( \mathfrak{h}_\mathbb{R} := P^\vee \otimes \mathbb{R} \). The weight lattice \( P \) is then defined by
\[
P := \{ \gamma \in \mathfrak{h}^* \mid \gamma(P^\vee) \subseteq \mathbb{Z} \}.
\]
Set \( S^\vee := \{h_1, \ldots, h_n\} \). One can then choose a set \( S := \{\alpha_1, \ldots, \alpha_n\} \) of linearly independent vectors in \( P \subseteq \mathfrak{h}^* \) such that \( \alpha_i(h_j) = a_{i,j} \) for \( i, j \in \{1, \ldots, n\} \) and \( \alpha_i(d_j) \in \{0, 1\} \) for \( i \in \{1, \ldots, n-r\} \). The elements of \( \Pi \) are the simple roots. The free abelian group \( Q := \bigoplus_{i=1}^n \mathbb{Z} \alpha_i \) is the root lattice. The quintuple \( (A, S, S^\vee, P, P^\vee) \) is called a generalized Cartan datum associated to the matrix \( A \). For any \( i = 1, \ldots, n \),
we also define the fundamental weight \( \omega_i \in P \) by \( \omega_i(h_j) = \delta_{ij} \) for \( j \in \{1, \ldots, n\} \) and \( \omega_i(d_j) = 0 \) for \( j \in \{1, \ldots, n - r\} \).

For any \( i = 1, \ldots, n \), we define the simple reflection \( s_i \) on \( \mathfrak{h}^* \) by

\[
(5) \quad s_i(\gamma) = \gamma - h_i(\gamma)\alpha_i \quad \text{for any } \gamma \in P.
\]

The Weyl group \( W \) is the subgroup of \( GL(\mathfrak{h}^*) \) generated by the reflections \( s_i \). Each element \( w \in W \) admits a reduced expression \( w = s_{i_1} \cdots s_{i_r} \). One can prove that \( r \) is independent of the reduced expression considered, so the signature \( \varepsilon(w) = (-1)^r \) is well defined.

**Definition 3.1.** The Kac-Moody algebra \( \mathfrak{g} \) associated to the quintuple \( (A, S, S', P, P') \) is the \( \mathbb{C} \)-algebra generated by the elements \( e_i, f_i, i = 1, \ldots, n \) and \( h \in P \) together with the relations

\[
\begin{align*}
(1) & \quad [h, h'] = 0 \text{ for any } h, h' \in P, \\
(2) & \quad [h, e_i] = \alpha_i(h)e_i \text{ for any } i = 1, \ldots, n \text{ and } h \in P, \\
(3) & \quad [h, f_i] = -\alpha_i(h)f_i \text{ for any } i = 1, \ldots, n \text{ and } h \in P, \\
(4) & \quad [e_i, f_j] = \delta_{ij}h_i \text{ for any } i, j = 1, \ldots, n, \\
(5) & \quad ad(e_i)^{1-a_{ij}}(e_j) = 0 \text{ for any } i, j = 1, \ldots, n \text{ such that } i \neq j, \\
(6) & \quad ad(f_i)^{1-a_{ij}}(f_j) = 0 \text{ for any } i, j = 1, \ldots, n \text{ such that } i \neq j,
\end{align*}
\]

where \( ad(a) \in \text{End}(\mathfrak{g}) \) is defined by \( ad(a)(b) = [a, b] := ab - ba \) for any \( a, b \in \mathfrak{g} \).

Denote by \( \mathfrak{g}_+ \) and \( \mathfrak{g}_- \) the subalgebras of \( \mathfrak{g} \) generated by the \( e_i \)'s and the \( f_i \)'s, respectively. We have the triangular decomposition \( \mathfrak{g} = \mathfrak{g}_+ \oplus \mathfrak{h} \oplus \mathfrak{g}_- \) and \( \mathfrak{h} \) is called the Cartan subalgebra of \( \mathfrak{g} \). For any \( \alpha \in Q \), set

\[
\mathfrak{g}_\alpha := \{ x \in \mathfrak{g} | [h, x] = \alpha(h)x \text{ for any } h \in \mathfrak{h} \}.
\]

The algebra \( \mathfrak{g} \) then decomposes on the form

\[
\mathfrak{g} = \bigoplus_{\alpha \in Q} \mathfrak{g}_\alpha
\]

where \( \dim \mathfrak{g}_\alpha \) is finite for any \( \alpha \in Q \). The roots of \( \mathfrak{g} \) are the nonzero elements \( \alpha \in Q \) such that \( \mathfrak{g}_\alpha \neq \{0\} \). We denote by \( R \) the set of roots of \( \mathfrak{g} \). Set \( Q_+ := \bigoplus_{i=1}^n \mathbb{Z}_{\geq 0} \alpha_i, \ R_+ := R \cap Q_+ \) and \( R_- = R \cap (-Q_+) \). Then one can prove that \( R = R_+ \cup R_- \) and \( R_- = -R_+ \) as for the finite-dimensional Lie algebras. For any \( \gamma = \sum_{i=1}^n a_i\alpha_i \in Q_+ \), we set

\[
ht(\gamma) := \sum_{i=1}^n a_i.
\]

We have the decomposition

\[
\mathfrak{g} = \bigoplus_{\alpha \in R_+} \mathfrak{g}_\alpha \oplus \mathfrak{h} \oplus \bigoplus_{\alpha \in R_-} \mathfrak{g}_\alpha.
\]

For any \( \alpha \in R_+ \), we set \( \dim \mathfrak{g}_\alpha = m_\alpha \) the multiplicity of the root \( \alpha \) in \( \mathfrak{g} \). The set \( R_+ \) is infinite as soon as \( A \) is not of finite type; the multiplicity \( m_\alpha \) may be greater than 1 but is always bounded as follows (see [6, §1.3]):

\[
(6) \quad m_\alpha \leq n^{ht(\alpha)} \quad \text{for any } \alpha \in R_+.
\]

When \( A \) is not of finite type, the Weyl group \( W \) is also infinite and there exist roots \( \alpha \in R \) which do not belong to any orbit \( W\alpha_i, i = 1, \ldots, n \) of a simple root; these
roots are called *imaginary roots* in contrast to *real roots* which belong to the orbit of a simple root \( \alpha_i \).

The root system associated to a matrix \( A \) of finite type is well known (see for instance [2]) and is classified into four infinite series \((A_n, B_n, C_n \text{ and } D_n)\) and five exceptional systems \((E_6, E_7, E_8, F_4, G_2)\). In contrast, little is known about the root system associated to a matrix of indefinite type. In the intermediate case of the affine matrices, there also exists a finite classification which yields seven infinite series and seven exceptional systems. The root system can be described as follows.

First, the rows and columns of \( A \) can be ordered such that the submatrix \( A^\circ \) of size \((n - 1) \times (n - 1)\) obtained by deleting the row and column indexed by \( n \) in \( A \) is the Cartan matrix of a finite root system \( R^\circ \). The kernel of \( A \) has dimension 1; more precisely, there exists a unique \( n \)-tuple \((a_1, \ldots, a_n)\) of positive relatively prime integers such that \( A' \) \((a_1, \ldots, a_n) \equiv 0 \) and the vector \( \delta = \sum_{i=1}^{n} a_i \alpha_i \) then belongs to \( R \). The sets of real roots, of imaginary roots and of positive imaginary roots can be completely described in terms of roots in \( R^\circ \) and \( \delta \). We refer to [6, p. 83] for a complete exposition and only recall the following facts we need in the sequel. In particular, we do not need the complete description of the sets \( R^\circ_+ \) which strongly depends on the affine root system considered. We have

\[
R^\circ_+ \subset \{ \alpha + k\delta \mid \alpha \in R^\circ, k \in \mathbb{Z}_{>0} \} \cup R^\circ
\]

except for the affine root system \( A_{2n}^{(2)} \), in which case

\[
R^\circ_+ \subset \{ \alpha + k\delta \mid \alpha \in R^\circ, k \in \mathbb{Z}_{>0} \} \cup \{ \frac{1}{2}(\alpha + (2k - 1)\delta) \mid \alpha \in R^\circ, k \in \mathbb{Z}_{>0} \} \cup R^\circ.
\]

We also have in all affine cases

\[
(7) \quad R^\circ_+ \subset \{ k\delta \mid k \in \mathbb{Z}_{>0} \} \quad \text{and} \quad R_+ = R^\circ_+ \cup R^\circ.
\]

The multiplicities of the positive roots verify (see [6, Corollary 8.3])

\[
(8) \quad m_\alpha = 1 \text{ for } \alpha \in R^\circ_+ \quad \text{and} \quad m_\alpha \leq n \text{ for } \alpha \in R^\circ.
\]

**3.2. The category \( O_{\text{int}} \) of \( g \)-modules.** Let \( g \) be a symmetrizable Kac-Moody algebra. We now introduce a category of \( g \)-modules whose properties naturally extend those of the finite-dimensional representations of simple Lie algebras.

**Definition 3.2.** The category \( O_{\text{int}} \) is the category of \( g \)-modules \( M \) satisfying the following properties:

1. The module \( M \) decomposes in weight subspaces on the form
   \[
   M = \bigoplus_{\gamma \in P} M_\gamma \text{ where } M_\gamma := \{ v \in M \mid h(v) = \gamma(h)v \text{ for any } h \in \mathfrak{h} \}.
   \]
2. For any \( i = 1, \ldots, n \), the actions of \( e_i \) and \( f_i \) are locally nilpotent; i.e. for any \( v \in M \) there exist integers \( p \) and \( q \) such that \( e_i^p \cdot v = f_i^q \cdot v = 0 \).

For any \( \gamma \in P \), let \( e^\gamma \) be the generator of the group algebra \( \mathbb{C}[P] \) associated to \( \gamma \). By definition, we have \( e^\gamma e^\gamma' = e^{\gamma + \gamma'} \) for any \( \gamma, \gamma' \in P \) and the group \( W \) acts on \( \mathbb{C}[P] \) as follows: \( w(e^\gamma) = e^{w(\gamma)} \) for any \( w \in W \) and any \( \gamma \in P \).

The irreducible modules in the category \( O_{\text{int}} \) are the irreducible highest weight modules; they are parametrized by the *integral cone of dominant weights* \( P_+ \) of \( g \) defined by

\[
P_+ := \{ \lambda \in P \mid \lambda(h_i) \geq 0 \text{ for any } i = 1, \ldots, n \}.
\]
The irreducible highest weight module \( V(\lambda) \) of weight \( \lambda \in P_+ \) decomposes as 
\[
V(\lambda) = \bigoplus_{\gamma \in P} V(\lambda)_\gamma;
\]
observe that \( \dim V(\lambda) \) is infinite when \( \mathfrak{g} \) is not of finite type. Nevertheless the weight space \( V(\lambda)_\gamma \) is always finite-dimensional, and we set 
\[
K_{\lambda,\gamma} := \dim V(\lambda)_\gamma.
\]
Furthermore, we have \( \dim V(\lambda) = 1 \) and \( e_i(v) = 0 \) for any \( i = 1, \ldots, n \) and \( v \in V(\lambda)_\lambda \); the elements of \( V(\lambda)_\lambda \) thus coincide up to a multiplication by a scalar and are called the highest weight vectors.

The character \( s_\lambda \) of \( V(\lambda) \) is defined by \( s_\lambda := \sum_{\gamma \in P} K_{\lambda,\gamma} e^\gamma \); it is invariant under the action of the Weyl group \( W \) since \( K_{\lambda,\gamma} = K_{\lambda,w(\gamma)} \) for any \( w \in W \). Observe that the orbit \( W \cdot \gamma \) intersects \( P_+ \) exactly once when \( K_{\lambda,\gamma} > 0 \).

From now on, we fix a weight \( \rho \in P \) such that \( \rho(h_i) = 1 \) for any \( i = 1, \ldots, n \); we have the Kac-Weyl character formula:

**Theorem 3.3.** For any \( \lambda \in P_+ \), we have 
\[
s_\lambda = \frac{\sum_{w \in W} \varepsilon(w) e^{w(\lambda+\rho) - \rho}}{\prod_{\alpha \in R_+} (1 - e^{-\alpha})^{m_\alpha}}.
\]

The category \( \mathcal{O}_{\text{int}} \) is stable under the tensor product of \( \mathfrak{g} \)-modules. Moreover, every module \( M \in \mathcal{O}_{\text{int}} \) that decomposes has a direct sum of irreducible modules. Given \( \lambda(1), \ldots, \lambda(k) \) a sequence of dominant weights, consider the module 
\[
M := V(\lambda(1)) \otimes \cdots \otimes V(\lambda(k)).
\]
Then \( M_\pi \) is finite for any \( \gamma \in P \), the character of \( M \) can be defined by 
\[
\text{char}(M) := \sum_{\gamma \in P} \dim M_\gamma e^\gamma
\]
and we have 
\[
\text{char}(M) = s_{\lambda(1)} \cdots s_{\lambda(k)}.
\]
Each irreducible component of \( M \) appears finitely many times in this decomposition; in other words there exist nonnegative integers \( m_{M,\lambda} \) such that 
\[
M \simeq \bigoplus_{\lambda \in P_+} V(\lambda) \otimes^{m_{M,\lambda}} \text{ or equivalently } \text{char}(M) := \sum_{\lambda \in P_+} m_{M,\lambda} s_\lambda.
\]
Consider \( \kappa, \mu \in P_+ \) and \( \ell \in \mathbb{Z}_{\geq 0} \). We set 
\[
V(\mu) \otimes V(\kappa) \otimes^{\ell} = \sum_{\lambda \in P_+} V(\lambda) \otimes f^{\kappa,\ell}_{\lambda/\mu} \text{ and } m_{\mu,\kappa}^{\lambda} = f^{\kappa,\ell}_{\lambda/\mu}.
\]
In the sequel, we will fix \( \kappa \in P_+ \) and write \( f^{\kappa,\ell}_{\lambda/\mu} = f^{\ell}_{\lambda/\mu} \) for short.

### 3.3. Littelmann path model

The aim of this paragraph is to give a brief overview of the path model developed by Littelmann and its connections with Kashiwara crystal basis theory. We refer to [12], [13], [14] and [7] for examples and a detailed exposition. Let \( \mathfrak{g} \) be a symmetrizable Kac-Moody algebra associated to the quintuple \( (A, S, S^\vee, P, P^\vee) \) where \( A \) is an \( n \times n \) symmetrizable generalized Cartan matrix with rank \( r \). In the following, it will be convenient to fix a nondegenerate symmetric bilinear form \( \langle \cdot, \cdot \rangle \) on \( \mathfrak{h}_R^* \) invariant under \( W \). This permits us to identify \( \mathfrak{h}_R^* \) and \( \mathfrak{h}_R \). Let \( \|\| \) be any choice of norm on \( \mathfrak{h}_R^* \). For any root \( \alpha \), we set \( \alpha^\vee = \frac{\alpha}{\langle \alpha, \alpha \rangle} \). We have seen that \( P \) is a \( \mathbb{Z} \)-lattice with rank \( d = 2n - r \). We define the notion of elementary piecewise linear paths in \( P_R := P \otimes_{\mathbb{Z}} \mathbb{R} \) as we did in subsection 2.2.

Let \( \mathcal{L} \) be the set of such elementary paths having only rational turning points (i.e. whose inflexion points have rational coordinates) and ending in \( P \), i.e. such that \( \pi(1) \in P \). The Weyl group \( W \) acts on \( \mathcal{L} \) as follows: for any \( w \in W \) and \( \eta \in \mathcal{L} \), the path \( w[\eta] \) is defined by 
\[
\forall t \in [0, 1] \quad w[\eta](t) = w(\eta(t)),
\]
and the weight \( \text{wt}(\eta) \) of \( \eta \) is defined by \( \text{wt}(\eta) = \eta(1) \).
We now define operators \( \tilde{e}_i \) and \( \tilde{f}_i, \ i = 1, \ldots, n, \) acting on \( \mathcal{L} \cup \{0\} \). If \( \eta = 0 \), we set \( \tilde{e}_i(\eta) = \tilde{f}_i(\eta) = 0 \); when \( \eta \in \mathcal{L} \), we need to decompose \( \eta \) into a union of finitely many subpaths and reflect some of these subpaths by \( s_\alpha \), according to the behavior of the map

\[
\tilde{h}_\eta : \begin{cases} [0,1] & \to \mathbb{R} \\ t & \mapsto \langle \eta(t), \alpha \rangle. \end{cases}
\]

Let \( m_\eta \) be the minimum of the function \( h_\eta \). Since \( h_\eta(0) = 0 \), we have \( m_\eta \leq 0 \).

If \( m_\eta > -1 \), then \( \tilde{e}_i(\eta) = 0 \). If \( m_\eta \leq -1 \), set \( t_1 := \inf \{t \in [0,1] \mid h_\eta(t) = m_\eta\} \) and let \( t_0 \in (0, t_1) \) be maximal such that \( m_\eta \leq h_\eta(t) \leq m_\eta + 1 \) for any \( t \in [t_0, t_1] \) (see Figure 1). Choose \( r \geq 1 \) and \( t_0 = t^{(0)} < t^{(1)} < \cdots < t^{(r)} = t_1 \) satisfying the following conditions: for \( 1 \leq a \leq r \),

1. either \( h_\eta(t^{(a-1)}) = h_\eta(t^{(a)}) \) and \( h_\eta(t) \geq h_\eta(t^{(a)}) \) on \( [t^{(a-1)}, t^{(a)}] \),
2. or \( h_\eta \) is strictly decreasing on \( [t^{(a-1)}, t^{(a)}] \) and \( h_\eta(t) \geq h_\eta(t^{(a-1)}) \) on \( [0,t^{(a-1)}] \).

We set \( t^{(-1)} = 0 \) and \( t^{(r+1)} = 1 \) and, for \( 0 \leq a \leq r+1 \), we denote by \( \eta_a \) the elementary path defined by

\[
\forall \eta_a \in [0,1] \quad \eta_a(u) = \eta(t^{(a-1)} + u(t^{(a)} - t^{(a-1)})) - \eta(t^{(a-1)}).
\]

Observe that \( \eta_a \) is the elementary path whose image translated by \( \eta(t^{(a-1)}) \) coincides with the restriction of \( \eta \) on \( [t^{(a-1)}, t^{(a)}] \); the path \( \eta \) decomposes as

\[
\eta = \eta_0 * \eta_1 * \cdots * \eta_r * \eta_{r+1}.
\]

For \( 1 \leq a \leq r+1 \), we also set \( \eta'_a = \eta_a \) in case (1) and \( \eta'_a = s_{\alpha_i}(\eta_a) \) in case (2). For \( i \in \{1, \ldots, n\} \), we set

\[
\tilde{e}_i(\eta) = \begin{cases} 0 & \text{if } h_\eta(1) < m_\eta + 1, \\ \eta_0 * \eta'_1 * \cdots * \eta'_r * \eta_{r+1} & \text{otherwise.} \end{cases}
\]

To define the \( \tilde{f}_i \), we first propose another decomposition of the path \( \eta \). If \( h_\eta(1) < m_\eta + 1 \), then \( \tilde{f}_i(\eta) = 0 \). Otherwise \( h_\eta(1) \geq m_\eta + 1 \), set \( t'_0 := \sup \{t \in [0,1] \mid h_\eta(t) = m_\eta\} \) and let \( t'_1 \in [t'_0, 1] \) be minimal such that \( h_\eta(t) \geq m_\eta + 1 \) for \( t \in [t'_1, 1] \) (see Figure 1). Choose \( r \geq 1 \) and \( t'_0 = t^{(0)} < t^{(1)} < \cdots < t^{(r)} = t'_1 \) satisfying the following conditions: for \( 1 \leq a \leq r \),

1. either \( h_\eta(t^{(a-1)}) = h_\eta(t^{(a)}) \) and \( h_\eta(t) \geq h_\eta(t^{(a)}) \) on \( [t^{(a-1)}, t^{(a)}] \),
2. or \( h_\eta \) is strictly increasing on \( [t^{(a-1)}, t^{(a)}] \) and \( h_\eta(t) \geq h_\eta(t^{(a-1)}) \) on \( [t^{(a-1)}, t^{(a)}] \).

We set \( t^{(-1)} = 0 \) and \( t^{(r+1)} = 1 \) and, for \( 0 \leq a \leq r+1 \), we denote by \( \eta_a \) the elementary path defined by

\[
\forall \eta_a \in [0,1] \quad \eta_a(u) = \eta(t^{(a-1)} + u(t^{(a)} - t^{(a-1)})) - \eta(t^{(a-1)}).
\]

As above, the path \( \eta \) decomposes as \( \eta = \eta_0 * \eta_1 * \cdots * \eta_r * \eta_{r+1} \); for \( 1 \leq a \leq r+1 \), we thus set \( \eta'_a = \eta_a \) in case (3) and \( \eta'_a = s_{\alpha_i}(\eta_a) \) in case (4), and the operator \( \tilde{f}_i, 1 \leq i \leq n \), is defined by

\[
\tilde{f}_i(\eta) = \begin{cases} 0 & \text{if } h_\eta(1) < m_\eta + 1, \\ \eta_0 * \eta'_1 * \cdots * \eta'_r * \eta_{r+1} & \text{otherwise.} \end{cases}
\]

**Remarks.** 1. When \( g \) is finite-dimensional, the symmetric bilinear form \( \langle \cdot, \cdot \rangle \) can be assumed positive so that elements of \( W \) are isometries. The paths \( \eta, \tilde{e}_i(\eta) \) and \( \tilde{f}_i(\eta) \) have the same length. This is no longer true when \( g \) is of affine or indefinite type.
2. When $\tilde{e}_i(\eta)$ is computed, the segments of $\eta$ which are replaced by their symmetries under $s_{\alpha_i}$ correspond to intervals where $h_\eta$ is strictly decreasing. This implies that $h_\eta(t) \leq h_{\tilde{e}_i(\eta)}(t)$ for any $t \in [0, 1]$. Similarly, we have $h_\eta(t) \geq h_{\tilde{f}_i(\eta)}(t)$ for any $t \in [0, 1]$.

The operators $\tilde{e}_i$ and $\tilde{f}_i$ satisfy the following properties:

**Proposition 3.4.**

1. Assume $\tilde{e}_i(\eta) \neq 0$; then $\tilde{e}_i(\eta)(1) = \eta(1) + \alpha_i$ and $\tilde{f}_i(\tilde{e}_i(\eta)) = \eta$.
2. Assume $\tilde{f}_i(\eta) \neq 0$; then $\tilde{f}_i(\eta)(1) = \eta(1) - \alpha_i$ and $\tilde{e}_i(\tilde{f}_i(\eta)) = \eta$.
3. A path $\eta \in \mathcal{L}$ satisfies $\tilde{e}_i(\eta) = 0$ for any $i = 1, \ldots, n$ if and only if $\text{Im} \eta + \rho$ is contained in $\hat{\mathcal{C}}$.

**Remark.** It also directly follows from the definition of $\tilde{f}_i(\eta)$ that there exists a piecewise linear increasing map $g$ defined on $[0, 1]$ satisfying

$$(11) \quad \eta(t) - \tilde{f}_i(\eta)(t) = g(t)\alpha_i \quad \text{for any } t \in [0, 1]$$

and $g(0) = 0$, $g(1) = 1$. 

**Figure 1.** Paths $\eta$, $\eta_1 = \tilde{e}_i(\eta)$ and $\eta_2 = \tilde{f}_i(\eta)$
We may endow $\mathcal{L}$ with the structure of a Kashiwara crystal: this means that $\mathcal{L}$ has the structure of a colored oriented graph by drawing an arrow $\eta \rightarrow \eta'$ between the two paths $\eta, \eta'$ of $\mathcal{L}$ as soon as $\tilde{f}_i(\eta) = \eta'$ (or equivalently $\tilde{e}_i(\eta')$). For any $\eta \in \mathcal{L}$, we denote by $B(\eta)$ the connected component of $\eta$, i.e. the subgraph of $\mathcal{L}$ obtained by applying operators $\tilde{e}_i$ and $\tilde{f}_i$, $i = 1, \ldots, n$ to $\eta$.

For any path $\eta \in \mathcal{L}$ and $i = 1, \ldots, n$, set $\varepsilon_i(\eta) = \max\{k \in \mathbb{Z}_{\geq 0} \mid \tilde{e}_i^k(\eta) = 0\}$ and $\varphi_i(\eta) = \max\{k \in \mathbb{Z}_{\geq 0} \mid \tilde{f}_i^k(\eta) = 0\}$; one easily checks that $\varepsilon_i(\eta)$ and $\varphi_i(\eta)$ are finite.

We now introduce the following notation:

- $\mathcal{L}_{\text{int}}$ is the set of integral paths, that is, paths $\eta$ such that $m_\eta = \min_{t \in [0, 1]} \{(\eta(t), \alpha_i^\vee)\}$ belongs to $\mathbb{Z}$ for any $i = 1, \ldots, n$.
- $\hat{C}$ is the cone in $\mathfrak{h}_R^*$ defined by $\mathcal{C} = \{x \in \mathfrak{h}_R^* \mid x(h_i) \geq 0\}$.
- $\check{C}$ is the interior of $C$; it is defined by $\check{C} = \{x \in \mathfrak{h}_R^* \mid x(h_i) > 0\}$.

One gets the following:

**Proposition 3.5.** Let $\eta$ and $\pi$ be two paths in $\mathcal{L}_{\text{int}}$. Then

1. the concatenation $\pi * \eta$ belongs to $\mathcal{L}_{\text{int}}$,
2. for any $i = 1, \ldots, n$ we have
   \[
   \tilde{e}_i(\eta * \pi) = \begin{cases} 
   \eta * \tilde{e}_i(\pi) & \text{if } \varepsilon_i(\pi) > \varphi_i(\eta), \\
   \tilde{e}_i(\eta) * \pi & \text{otherwise,}
   \end{cases}
   \]
   \[
   \tilde{f}_i(\eta * \pi) = \begin{cases} 
   \tilde{f}_i(\eta) * \pi & \text{if } \varphi_i(\eta) > \varepsilon_i(\pi), \\
   \eta * \tilde{f}_i(\pi) & \text{otherwise.}
   \end{cases}
   \]
3. $\tilde{e}_i(\eta) = 0$ for any $i = 1, \ldots, n$ if and only if $\varepsilon_i(\eta) = 0$ and $\varepsilon_i(\pi) \geq \varphi_i(\eta)$ for any $i = 1, \ldots, n$.

The following theorem summarizes crucial results of Littelmann (see [12], [13] and [14]).

**Theorem 3.6.** Consider $\lambda, \mu$ and $\kappa$ dominant weights and choose arbitrarily elementary paths $\eta_\lambda, \eta_\mu$ and $\eta_\kappa$ in $\mathcal{L}$ such that $\text{Im} \eta_\lambda \subset \mathcal{C}$, $\text{Im} \eta_\mu \subset \mathcal{C}$ and $\text{Im} \eta_\kappa \subset \mathcal{C}$ and joining respectively 0 to $\lambda$, 0 to $\mu$ and 0 to $\kappa$.

1. We have $B(\eta_\lambda) := \{\tilde{f}_i \cdots \tilde{f}_i \eta_\lambda \mid k \in \mathbb{N} \text{ and } 1 \leq i_1, \ldots, i_k \leq n\} \setminus \{0\}$. In particular $\text{wt}(\eta) - \text{wt}(\eta_\lambda) \in Q_+$ for any $\eta \in B(\eta_\lambda)$.
2. The graph $B(\eta_\lambda)$ is contained in $\mathcal{L}_{\text{int}}$.
3. If $\eta'_\lambda$ is another elementary path from 0 to $\lambda$ such that $\text{Im} \eta'_\lambda$ is contained in $\mathcal{C}$, then $B(\eta_\lambda)$ and $B(\eta'_\lambda)$ are isomorphic as oriented graphs; i.e. there exists a bijection $\theta : B(\eta_\lambda) \rightarrow B(\eta'_\lambda)$ which commutes with the action of the operators $\tilde{e}_i$ and $\tilde{f}_i$, $i = 1, \ldots, n$.
4. The crystal $B(\eta_\lambda)$ is isomorphic to the Kashiwara crystal graph $B(\lambda)$ associated to the $U_q(\mathfrak{g})$-module of highest weight $\lambda$.
5. We have
   \[
   s_\lambda = \sum_{\eta \in B(\eta_\lambda)} e^{\eta(1)}.
   \]
6. For any $i = 1, \ldots, n$ and any $b \in B(\eta_\lambda)$, let $s_i(b)$ be the unique path in $B(\eta_\lambda)$ such that
   \[
   \varphi_i(s_i(b)) = \varepsilon_i(b) \text{ and } \varepsilon_i(s_i(b)) = \varphi_i(b).
   \]
is a formal power series in the variables $B$ in general. Consider $\gamma$ \textsuperscript{15}

Now, since $\gamma$ \textsuperscript{5,20.7} instance $[5,\ldots]$ contains only the paths $\pi = \eta \ast \eta_1 \ast \cdots \ast \eta_\ell \in \mathcal{L} | \eta \in B(\eta_\mu)$ and $\eta_k \in B(\eta_\kappa)$ for any $k = 1, \ldots, \ell$.

The graph $B(\eta_\mu) \ast B(\eta_\kappa)^{\ast \ell}$ is contained in $\mathcal{L}_{\min \mathbb{Z}}$.

The multiplicity $m_{\lambda,\kappa}^{\ast \ell}$ defined in \textsuperscript{9} is equal to the number of paths of the form $\mu \ast \eta$ with $\eta \in B(\eta_\kappa)$ contained in $\mathcal{C}$.

The multiplicity $f_{\lambda/\mu}^\ell$ defined in \textsuperscript{9} is equal to cardinality of the set $H_{\lambda/\mu}^\ell := \{ \pi \in B(\eta_\mu) \ast B(\eta_\kappa)^{\ast \ell} | \tilde{e}_i(\pi) = 0 \text{ for any } i = 1, \ldots, n \text{ and } \pi(1) = \lambda \}$. Each path $\pi = \eta \ast \eta_1 \ast \cdots \ast \eta_\ell \in H_{\lambda/\mu}^\ell$ verifies $\Im \pi \subset \mathcal{C}$ and $\eta = \eta_\mu$.

Remarks. 1. Combining assertion (2) of Proposition \textsuperscript{3.4} together with assertions (1) and (5) of Theorem \textsuperscript{3.6} one may check that the function $e^{-\lambda} s_\lambda$ is in fact a polynomial in the variables $T_i = e^{-\alpha_i}$, namely

\begin{equation}
\lambda = e^\lambda S_\lambda(T_1, \ldots, T_n)
\end{equation}

where $S_\lambda \in \mathbb{C}[X_1, \ldots, X_n]$. Observe also that the quantity $S_\infty := \prod_{\alpha \in R_+} \frac{1}{[1-e^{-\alpha}]^{m_\alpha}}$ is a formal power series in the variables $T_1, \ldots, T_n$. M. Kashiwara proved (see for instance \textsuperscript{5,20.7}) that the crystal $B(\lambda)$ admits a projective limit $B(\infty)$ when $\lambda$ tends to infinity and that \begin{equation}
\text{char}(B(\infty)) = \sum_{b \in B(\infty)} e^{\text{wt}(b)} = S_\infty.
\end{equation}

Now, since $B(\lambda)$ can be embedded in $B(\infty)$ up to a translation by the weights of $\lambda$, we have

\begin{equation}
S_\lambda(T_1, \ldots, T_n) \leq S_\infty(T_1, \ldots, T_n);
\end{equation}
in other words, $S_\infty(T_1, \ldots, T_n) = S_\lambda(T_1, \ldots, T_n) + \sum_{\mu \in Q_+} a_\mu T^\mu$ where the coefficients $a_\mu$ are nonnegative integers.

2. Using assertion (1) of Theorem \textsuperscript{3.6} we obtain $m_{\mu,\delta}^{\lambda} \neq 0$ only if $\mu + \delta - \lambda \in Q_+$. Similarly, when $f_{\lambda/\mu}^{\delta,\ell} \neq 0$ one necessarily has $\mu + \ell \delta - \lambda \in Q_+$.

3. A minuscule weight is a dominant weight $\kappa \in P_+$ such that the weights of $V(\kappa)$ are exactly those of the orbit $W \cdot \kappa$. In this case, if we take $\eta_\kappa : t \mapsto t \kappa$, the crystal $B(\eta_k)$ contains only the paths $\eta : t \mapsto t w(\kappa)$. In particular, these paths are lines. Conversely if $B(\eta_k)$ only contains lines, the weight $\kappa$ is minuscule. Indeed, consider $\gamma$ a weight of $V(\kappa)$. The orbit of $\gamma$ intersects $\mathcal{C}$ at say $\gamma_0$. Then the line $t \mapsto t \gamma_0$ is a path of $B(\eta_k)$. But $\eta_k$ is the unique path of $B(\eta_k)$ entirely contained in $\mathcal{C}$; therefore $\gamma_0 = \kappa$.

\textsuperscript{1}This action should not be confused with that defined in \textsuperscript{10} which does not stabilize $B(\eta_\kappa)$ in general.
4. Given any path $\eta_{\lambda}$ such that $\text{Im} \eta_{\lambda} \subset \mathcal{C}$, the set of paths $B(\eta_{\lambda})$ is in general very difficult to describe (even in the finite type cases). Nevertheless, for the classical types or type $G_2$ and a particular choice of $\eta_{\lambda}$, the sets $B(\eta_{\lambda})$ can be made explicit by using generalizations of semistandard tableaux (see for example [9] and the references therein).

The height $ht(\eta)$ of a Littelmann path $\eta \in B(\eta_{\lambda})$ is the length of any path in the crystal graph $B(\eta_{\lambda})$ from $\eta_{\lambda}$ to $\eta$. For any $a \geq 0$, we denote by $B(\eta_{\lambda})_a$ the set of paths in $B(\eta_{\lambda})$ at height $a$. Each subset $B(\eta_{\lambda})_a$ is finite and we have

$$B(\eta_{\lambda}) = \bigcup_{a \geq 0} B(\eta_{\lambda})_a.$$  

By Proposition 3.4, $ht(\eta)$ is equal to the number of simple roots appearing in the decomposition of $\text{wt}(\eta_{\lambda}) - \text{wt}(\eta)$ on the basis $\{\alpha_1, \ldots, \alpha_n\}$.

4. **Random paths and symmetrizable Kac-Moody algebras**

4.1. **Probability distribution on elementary paths.** Consider $\kappa \in P_+$ and a path $\pi_\kappa \in \mathcal{L}$ from 0 to $\kappa$ such that $\text{Im} \pi_\kappa$ is contained in $\mathcal{C}$. Let $B(\pi_\kappa)$ be the connected component of $\mathcal{L}$ containing $\pi_\kappa$. We now endow $B(\pi_\kappa)$ with a probability distribution $p_\kappa$, which will be characterized by the datum of an $n$-tuple $\tau = (\tau_1, \ldots, \tau_n) \in \mathbb{R}_{>0}^n$ (each $\tau_i$ can be regarded as attached to the positive simple root $\alpha_i$). For any $u = u_1\alpha_1 + \cdots + u_n\alpha_n \in Q$, we set $\tau^u = \tau_1^{u_1} \cdots \tau_n^{u_n}$. Let $\pi \in B(\pi_\kappa)$: by assertion (1) of Theorem 3.6 one gets

$$\pi(1) = \text{wt}(\pi) = \kappa - \sum_{i=1}^n u_i(\pi)\alpha_i$$

where $u_i(\pi) \in \mathbb{N}$ for any $i = 1, \ldots, n$. We have $S_\kappa(\tau) := S_\kappa(\tau_1, \ldots, \tau_n) = \sum_{\pi \in B(\pi_\kappa)} \tau^{\pi - \text{wt}(\pi)}$.

**Proposition 4.1.** For any $\kappa \in P_+$,

1. if $A$ is of finite type, then $0 < S_\kappa(\tau) < \infty$ for any $\tau \in \mathbb{R}_{>0}^n$,
2. if $A$ is of affine type, then $0 < S_\kappa(\tau) < \infty$ for any $\tau \in [0,1]^n$,
3. if $A$ is of indefinite type, then $0 < S_\kappa(\tau) < \infty$ for any $\tau \in [0,1]^n$.

**Proof.** The inequality $S_\kappa(\tau) > 0$ is immediate since $\tau_i > 0$ for any $i = 1, \ldots, n$. When $A$ is of finite type, the crystal $B(\pi_\kappa)$ is finite, so that $S_\kappa(\tau) < \infty$. When $A$ is not of finite type, let $\bar{\tau} = \max(\tau_i, i = 1, \ldots, n)$. We have by (16)

$$S_\kappa(\tau) \leq S_\kappa(\bar{\tau}) = \prod_{\alpha \in R_+} \frac{1}{(1 - \tau^\alpha)^{m_\alpha}} \leq \prod_{\alpha \in R_+} \frac{1}{(1 - \bar{\tau}^{ht(\alpha)})^{m_\alpha}},$$

and it suffices to prove that

$$S_\kappa(\bar{\tau}) = S_\infty(\bar{\tau}, \ldots, \bar{\tau}) = \prod_{\alpha \in R_+} \frac{1}{(1 - \bar{\tau}^{ht(\alpha)})^{m_\alpha}} < +\infty.$$
Assume first that \( A \) is of affine type different from \( A_{2n}^{(2)} \). By (7) and (8), we have

\[
\prod_{\alpha \in R_+} \frac{1}{(1 - \bar{\tau}^{ht(\alpha)})^{m_{\alpha}}} \leq \left( \prod_{\alpha \in R_+^\circ} \frac{1}{1 - \bar{\tau}^{ht(\alpha)}} \right) \left( \prod_{k=1}^{+\infty} \frac{1}{1 - \bar{\tau}^{kht(\delta)}} \right)
\]

since \( 0 < \bar{\tau} < 1 \) for any \( \alpha \in R_+ \) and \( R^\circ \) is finite. We have to prove that the infinite products in the above expression are finite. Since \( ht(\delta) \geq n \), we have \( \bar{\tau}^{ht(\delta)} \leq \bar{\tau}^n \); moreover \( \alpha + kr\delta \in \mathbb{Q}_+ \) for any \( k \geq 1 \) and \( \alpha \in R^\circ \). We therefore get

\[
\prod_{k=1}^{+\infty} \frac{1}{(1 - \bar{\tau}^{kht(\delta)})} \leq \left( \prod_{k=1}^{+\infty} \frac{1}{1 - \bar{\tau}^{kn}} \right)^n < +\infty
\]

since the series \( \sum_{k=1}^{+\infty} \ln(1 - \bar{\tau}^{kn}) \) converges for \( \bar{\tau}^n \in [0, 1] \). Similarly, since \( \bar{\tau}^m \in [0, 1] \) one gets

\[
\prod_{k=1}^{+\infty} \frac{1}{1 - \bar{\tau}^{ht(\alpha) + kr\delta}} \leq \prod_{k=1}^{+\infty} \frac{1}{1 - \bar{\tau}^{ht(\alpha) + kr\delta}} < +\infty.
\]

The case \( A_{2n}^{(2)} \) is obtained by the same arguments.

Secondly, assume that \( A \) is of indefinite type. By (9), we have

\[
S_\infty(\bar{\tau}) \leq \prod_{\alpha \in R_+} \frac{1}{(1 - \bar{\tau}^{ht(\alpha)})^{n^{ht(\alpha)}}}.
\]

Moreover, since \( 0 < \bar{\tau} < 1 \) for any \( \beta \in Q_+ \) and \( R_+ \subset \mathbb{Q}_+ \), we also have

\[
S_\infty^*(\bar{\tau}) \leq \prod_{\beta \in Q_+} \frac{1}{(1 - \bar{\tau}^{ht(\beta)})^{n^{ht(\beta)}}} = \prod_{k=1}^{+\infty} \frac{1}{1 - \bar{\tau}^{(k+1)n^k}}
\]

with

\[
\prod_{\beta \in Q_+} \frac{1}{(1 - \bar{\tau}^{k})^{n^k}} \leq \frac{1}{1 - \bar{\tau}^{k}}^{(k+1)n^k}
\]

since \( \text{card}(\{ \beta \in Q_+ | ht(\beta) = k \}) \leq (k + 1)^n \). We thus get

\[
S_\infty^*(\bar{\tau}) \leq \prod_{k=1}^{+\infty} \frac{1}{(1 - \bar{\tau}^{k})^{n^k(k+1)^n}} < +\infty
\]

using the fact that the series \( \sum_{k=1}^{+\infty} n^k(k+1)^n \ln(1 - \bar{\tau}^n) \) converges for \( \bar{\tau} \in [0, \frac{1}{n}] \).

The previous proposition has three important corollaries. First set

\[
T_\kappa(\tau) := T_\kappa(\tau_1, \ldots, \tau_n) = \sum_{\pi \in B(\pi_n)} h(\pi) \tau^{\kappa - \text{wt}(\pi)}.
\]

**Corollary 4.2.** For any \( \kappa \in \mathbb{P}_+ \),

1. if \( A \) is of finite type, then \( 0 < T_\kappa(\tau) < \infty \) for any \( \tau \in \mathbb{R}_{>0}^n \).
2. if \( A \) is of affine type, then \( 0 < T_\kappa(\tau) < \infty \) for any \( \tau \in [0, 1]^n \).
3. if \( A \) is of indefinite type, then \( 0 < T_\kappa(\tau) < \infty \) for any \( \tau \in [0, \frac{1}{n}]^n \).
**Proof.** This is clear when $A$ is of finite type. For assertions (2) and (3), let $\bar{\tau} = \max(\tau_i, i = 1, \ldots, n)$. In the previous proof, we have established that $S_{\infty}^*(\bar{\tau})$ is finite. Set $S_{\kappa}^*(\bar{\tau}) = S_{\kappa}(\bar{\tau}, \ldots, \bar{\tau})$. Since $S_{\kappa}^*(\bar{\tau}) \leq S_{\infty}^*(\bar{\tau})$, the series $S_{\kappa}^*(\bar{\tau})$ is also finite. This means that for any $\bar{\tau} \in [0, 1]$ we have

$$S_{\kappa}^*(\bar{\tau}) = \sum_{\bar{\pi} \in B(\pi_\kappa)} \bar{\tau}^{ht(\bar{\pi})} = \sum_{a \geq 0} m(a) \bar{\tau}^a < +\infty$$

where $m(a)$ is the number of paths in $B(\pi_\kappa)_a$ (see (17)). It follows that $T_{\kappa}^*(\bar{\tau}) = \sum_{a \geq 0} am(a) \bar{\tau}^a$ is also finite for any $\bar{\tau} \in [0, 1]$. Now we have

$$T_{\kappa}(\tau) \leq T_{\kappa}(\bar{\tau}, \ldots, \bar{\tau}) = \sum_{\bar{\pi} \in B(\pi_\kappa)} ht(\bar{\pi}) \bar{\tau}^{ht(\bar{\pi})} = T_{\kappa}^*(\bar{\tau}) < +\infty.$$ 

□

**Corollary 4.3.** For any $\mu \in P_+$ and $w \in W$, the weight $\mu + \rho - w(\mu + \rho)$ belongs to $Q_+$; moreover, for $\tau \in T$, one gets

$$\left| \sum_{w \in W} e(w) \tau^{\mu + \rho - w(\mu + \rho)} \right| \leq \sum_{w \in W} \tau^{\mu + \rho - w(\mu + \rho)} < +\infty.$$ 

**Proof.** By the Weyl-Kac character formula, one gets

$$e^{-\mu} s_\mu = \sum_{w \in W} e(w) \frac{e^{w(\mu + \rho) - \rho - \mu}}{\prod_{\alpha \in \Lambda_+}(1 - e^{-\alpha})^{m_\alpha}}.$$ 

Since $e^{-\mu} s_\mu$ and $\prod_{\alpha \in \Lambda_+}(1 - e^{-\alpha})^{m_\alpha}$ are polynomials in $e^{-\beta}$ with $\beta \in Q_+$, we have $\mu + \rho - w(\mu + \rho) \in Q_+$ for any $w \in W$. Now observe that $\mu + \rho$ belongs to $P_+$ and is the dominant weight of $V(\mu + \rho)$; each $w(\mu + \rho)$ is thus also a weight of $V(\mu + \rho)$. Therefore, the coefficients of the decomposition of $s_{\mu + \rho} - \sum_{w \in W} e^{w(\mu + \rho)}$ on the basis $\{e^\beta \mid \beta \in P\}$ are nonnegative; in other words $\sum_{w \in W} e^{w(\mu + \rho)} \leq s_{\mu + \rho}$, which readily implies that $\sum_{w \in W} e^{w(\mu + \rho) - \rho - \mu} \leq e^{\mu + \rho} - s_{\mu + \rho}$. By specializing $e^{-\alpha_i} = \tau_i$, one gets $\sum_{w \in W} \tau^{\mu + \rho - w(\mu + \rho)} \leq S_{\mu + \rho}(\tau) < +\infty.$ □

**Definition 4.4.** We define the probability distribution $p$ on $B(\pi_\kappa)$ by setting $p_\pi = \frac{\tau_\kappa^{\mu - wt(\pi)}}{S_{\kappa}(\tau)}$.

**Remark.** By assertion (3) of Theorem 3.6 for $\pi'_\kappa$ another elementary path from 0 to $\kappa$ such that $\text{Im} \pi'_\kappa$ is contained in $\mathcal{C}$, there exists an isomorphism $\Theta$ between the crystals $B(\pi_\kappa)$ and $B(\pi'_\kappa)$ and one gets $p_\pi = p_{\Theta(\pi)}$ for any $\pi \in B(\pi_\kappa)$. Therefore, the probability distributions we use on the graph $B(\pi_\kappa)$ are invariant by crystal isomorphisms.
Let $X$ be a random variable with values in $B(\pi_\kappa)$ and probability distribution $p$; as a direct consequence of Proposition 4.1, we get

**Corollary 4.5.** The variable $X$ admits a moment of order 1. Moreover the series of functions

$$m = \sum_{\pi \in B(\pi_\kappa)} p_{\pi} \pi$$

converges uniformly on $[0, 1]$.

**Proof.** We can decompose $B(\pi_\kappa) = \bigcup_{a \geq 0} B(\pi_\kappa)_a$ as in (17). Then, we get for any $t \in [0, 1]$,

$$m(t) = \sum_{a \geq 0} \sum_{\pi \in B(\pi_\kappa)_a} p_{\pi} \pi(t).$$

Consider $\pi \in B(\pi_\kappa)_a$ and set $\pi = \tilde{f}_1 \cdots \tilde{f}_n(\pi_\kappa)$. By (11) and an immediate induction, there exist increasing piecewise linear maps $g_1, \ldots, g_a$ from $[0, 1]$ to itself with $g_k(0) = 0$ and $g_k(1) = 1$ for any $k = 1, \ldots, a$ such that

$$\pi(t) = \pi_\kappa(t) - (g_1(t) \alpha_{i_1} + \cdots + g_a(t) \alpha_{i_a}).$$

In particular $\|\pi(t) - \pi_\kappa(t)\| \leq \|\alpha_1\| + \cdots + \|\alpha_a\| \leq Ca$ where $C = \max_{\alpha \in \pi} \|\alpha\|$ is the norm of the longest simple root. We thus get

$$\|\pi(t)\| \leq \|\pi_\kappa(t)\| + \|\pi(t) - \pi_\kappa(t)\| \leq \|\pi_\kappa\|_\infty + Ch(t(\pi)).$$

We obtain $\|p_{\pi} \pi\|_\infty \leq (\|\pi\|_\infty + Ch(\pi)\frac{\sum_{\pi \in B(\pi_\kappa)} \|\pi\|_\infty}{\sum_{\pi \in B(\pi_\kappa)} \|\pi\|_\infty})$. But the series

$$S_\kappa(\tau) = \sum_{\pi \in B(\pi_\kappa)} \tau^{\kappa - \wt(\pi)}$$

and $T_\kappa(\tau) = \sum_{\pi \in B(\pi_\kappa)} h t(\pi) \tau^{\kappa - \wt(\pi)}$

converge for $\|\cdot\|_\infty$ by Proposition 4.1 and Corollary 4.2. This means that the series of functions $m$ converges uniformly on $[0, 1]$. \qed

### 4.2. Random paths of arbitrary length.

We now extend the notion of elementary random paths. Assume that $\pi_1, \ldots, \pi_\ell$ is a family of elementary paths; the path $\pi_1 \otimes \cdots \otimes \pi_\ell$ of length $\ell$ is defined by: for all $k \in \{1, \ldots, \ell - 1\}$ and $t \in [k, k+1]$,

$$(19) \quad \pi_1 \otimes \cdots \otimes \pi_\ell(t) = \pi_1(1) + \cdots + \pi_k(1) + \pi_{k+1}(t - k).$$

Let $B^{\otimes \ell}(\pi_\kappa)$ be the set of paths of the form $b = \pi_1 \otimes \cdots \otimes \pi_\ell$ where $\pi_1, \ldots, \pi_\ell$ are elementary paths in $B(\pi_\kappa)$; there exists a bijection $\Delta$ between $B^{\otimes \ell}(\pi_\kappa)$ and the set $B^{\ast \ell}(\pi_\kappa)$ of paths in $L$ obtained by concatenations of $\ell$ paths of $B(\pi_\kappa)$:

$$(20) \quad \Delta : \begin{cases}
B^{\otimes \ell}(\pi_\kappa) & \rightarrow B^{\ast \ell}(\pi_\kappa) \\
\pi_1 \otimes \cdots \otimes \pi_\ell & \mapsto \pi_1 \ast \cdots \ast \pi_\ell.
\end{cases}$$

In fact $\pi_1 \otimes \cdots \otimes \pi_\ell$ and $\pi_1 \ast \cdots \ast \pi_\ell$ coincide up to a reparametrization, and we define the weight of $b = \pi_1 \otimes \cdots \otimes \pi_\ell$ by setting

$$\wt(b) := \wt(\pi_1) + \cdots + \wt(\pi_\ell) = \pi_1(1) + \cdots + \pi_\ell(1).$$

We now endow $B^{\otimes \ell}(\pi_\kappa)$ with the product probability measure $p^{\otimes \ell}$ defined by

$$(21) \quad p^{\otimes \ell}(\pi_1 \otimes \cdots \otimes \pi_\ell) = p(\pi_1) \cdots p(\pi_\ell) = \frac{\tau^{\ell(\kappa - (\pi_1(1) + \cdots + \pi_\ell(1)))}}{S_\kappa(\tau)^\ell} = \frac{\tau^{\ell(\kappa - \wt(b))}}{S_\kappa(\tau)^\ell}.$$  

In particular, for any $b, b'$ in $B^{\otimes \ell}(\pi_\kappa)$ such that $\wt(b) = \wt(b')$, one gets $p^{\otimes \ell}(b) = p^{\otimes \ell}(b')$. 


Write $\Pi_\ell : B^{\otimes \ell}(\pi_\kappa) \to B^{\otimes \ell-1}(\pi_\kappa)$ for the projection defined by

$$\Pi_\ell(\pi_1 \otimes \cdots \otimes \pi_{\ell-1} \otimes \pi_\ell) = \pi_1 \otimes \cdots \otimes \pi_{\ell-1};$$

the sequence $(B^{\otimes \ell}(\pi_\kappa), \Pi_\ell, p^{\otimes \ell})_{\ell \geq 1}$ is a projective system of probability spaces. We denote by $(B^{\otimes N}(\pi_\kappa), p^{\otimes N})$ its injective limit; the elements of $B^{\otimes N}(\pi_\kappa)$ are infinite sequences $b = (\pi_\ell)_{\ell \geq 1}$, and by a slight abuse of notation, we will also write $\Pi_\ell(b) = \pi_1 \otimes \cdots \otimes \pi_\ell$.

Now let $X = (X_\ell)_{\ell \geq 1}$ be a sequence of i.i.d. random variables with values in $B(\pi_\kappa)$ and probability distribution $p$; the random path $W$ on $(B^{\otimes N}(\pi_\kappa), p^{\otimes N})$ are thus defined by

$$W(t) := \Pi_\ell(X(t)) = X_1 \otimes X_2 \otimes \cdots \otimes X_{\ell-1} \otimes X_\ell(t) \text{ for } t \in [\ell - 1, \ell].$$

By (19), the path $W$ coincides with the one defined in subsection 2.3. The following proposition is a probabilistic reformulation of the properties of the Littelmann path model.

**Proposition 4.6.**

1. For any $\beta, \eta \in P$, one gets

$$P(W_{\ell+1} = \beta \mid W_\ell = \eta) = K_{\kappa, \beta-\eta}^{\tau_{\kappa+\eta-\beta}} S_{\kappa}(\tau).$$

2. Consider $\lambda, \mu \in P^+$; we have

$$P(W_\ell = \lambda, W_0 = \mu, W(t) \in C \text{ for any } t \in [0, \ell]) = \int_{\lambda/\mu}^{\ell_{\kappa+\mu-\lambda}} \frac{S_{\kappa}(\tau)}{\tau_{\kappa+\mu-\lambda}}. $$

In particular,

$$P(W_{\ell+1} = \lambda, W_\ell = \mu, W(t) \in C \text{ for any } t \in [\ell, \ell+1]) = m_{\lambda, \mu}^{\lambda_{\kappa+\mu-\lambda}} S_{\kappa}(\tau).$$

**Proof.** (1) We have

$$P(W_{\ell+1} = \beta \mid W_\ell = \eta) = \sum_{\pi \in B(b_\pi)_{\beta-\eta}} p_\pi$$

where $B(b_\pi)_{\beta-\eta}$ is the set of paths in $B(b_\pi)$ of weight $\beta - \eta$. We conclude by noticing that all the paths in $B(b_\pi)_{\beta-\eta}$ have the same probability $\frac{\tau_{\kappa+\eta-\beta}}{S_{\kappa}(\tau)}$ and $\text{card}(B(b_\pi)_{\beta-\eta}) = K_{\kappa, \beta-\eta}$.

(2) By assertion (7) of Theorem 3.6, we know that the number of paths in $B(\pi_\mu) \ast B^{\otimes \ell}(\pi_\kappa)$ starting at $\mu$, ending at $\lambda$ and remaining in $C$ is equal to $f^{\ell}_{\lambda/\mu}$. Since the map $\Delta$ defined in (20) is a bijection, the integer $f^{\ell}_{\lambda/\mu}$ is also equal to the number of paths in $B(\pi_\mu) \otimes B^{\otimes \ell}(\pi_\kappa)$ starting at $\mu$, ending at $\lambda$ and remaining in $C$. Moreover, each such path has the form $b = b_\mu \otimes b_1 \otimes \cdots \otimes b_\ell$ where $b_1 \otimes \cdots \otimes b_\ell$ is the unique path in $B^{\otimes \ell}(\pi_\kappa)$ has weight $\lambda - \mu$. Therefore we have $p_\mu = \frac{f^{\ell}_{\lambda/\mu}}{S_{\kappa}(\tau)}$. □

### 4.3. The generalized Pitman transform

By assertion (8) of Theorem 3.6, we know that $B^{\otimes \ell}(\pi_\kappa)$ is contained in $L_{\min, Z}$. Therefore, if we consider a path $b \in B^{\otimes \ell}(\pi_\kappa)$, its connected component $B(b)$ is contained in $L_{\min, Z}$. Now, if $\eta \in B(b)$ is such that $\tilde{c}_i(\eta) = 0$ for any $i = 1, \ldots, n$, we should have $\text{Im} \eta \subset C$ by assertion (3) of Proposition 3.3. Assertion (1) of Theorem 3.6 thus implies that $\eta$ is the unique path in $B(b) = B(\eta)$ such that $\tilde{c}_i(\eta) = 0$ for any $i = 1, \ldots, n$. This permits us to define the **generalized Pitman transform** on $B^{\otimes \ell}(\pi_\kappa)$ as the map $\mathcal{P}$ which associates to any
For any $b \in B^\otimes \ell (\pi_\kappa)$ the unique path $\mathcal{P}(b) \in B(b)$ such that $\tilde{e}_i(\eta) = 0$ for any $i = 1, \ldots, n$. By definition, we have $\text{Im} \mathcal{P}(b) \subset C$ and $\mathcal{P}(b(\ell)) \in P_+$. 

Let $\mathcal{W}$ be the random path of subsection 4.2. We define the random process $\mathcal{H}$ setting

\begin{equation}
\mathcal{H}(t) = \mathcal{P}(\Pi_t(\mathcal{W}))(t) \text{ for any } t \in [\ell - 1, \ell].
\end{equation}

For any $\ell \geq 1$, we set $H_\ell := \mathcal{H}(\ell)$; one gets the following:

**Theorem 4.7.** The random sequence $H := (H_\ell)_{\ell \geq 1}$ is a Markov chain with transition matrix

\begin{equation}
\Pi(\mu, \lambda) = \frac{S(\lambda)}{S(\lambda)S(\mu)} \tau^{\kappa + \mu - \lambda} m_{\mu, \kappa}.
\end{equation}

where $\lambda, \mu \in P_+$.

**Proof.** Consider $\mu = \mu^{(\ell)} , \mu^{(\ell - 1)} , \ldots , \mu^{(1)}$ a sequence of elements in $P_+$. Let $S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)$ be the set of paths $b^h \in B^\otimes \ell (\pi_\kappa)$ remaining in $C$ and such that $b^h(k) = \mu^{(k)}, k = 1, \ldots, \ell$ and $b^{(\ell + 1)} = \lambda$. Consider $b = b_1 \otimes \cdots \otimes b_\ell \otimes b_{\ell + 1} \in B^\otimes \ell + 1 (\pi_\kappa)$. We have $P(b_1 \cdots \otimes b_k)(k) = \mu^{(k)}$ for any $k = 1, \ldots, \ell$ and $P(b(\ell + 1) = \lambda$ if and only if $P(b) \in S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)$. Moreover, by (21), for any $b^h \in S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)$, we have $P(b \in B(b^h)) = \sum_{b \in B(b^h)} p_b = \sum_{b \in B(b^h)} S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda) S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda) \frac{S(\lambda)}{S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)}$, which only depends on $\lambda$. This gives

\begin{equation}
P(H_{\ell + 1} = \lambda, H_k = \mu^{(k)}, \forall k = 1, \ldots, \ell) = \sum_{b^h \in S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)} \sum_{b \in B(b^h)} p_b = \text{card}(S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)) \frac{S(\lambda)}{S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)}.
\end{equation}

By assertion (9) of Theorem 3.6 and an easy induction, we also have

\begin{equation*}
\text{card}(S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)) = \prod_{k=1}^{\ell-1} m_{\mu^{(k+1)}, \kappa} \times m_{\mu, \kappa}.
\end{equation*}

We thus get

\begin{equation*}
P(H_{\ell + 1} = \lambda, H_k = \mu^{(k)}, \forall k = 1, \ldots, \ell) = \prod_{k=1}^{\ell-1} m_{\mu^{(k+1)}, \kappa} \times m_{\mu, \kappa} \frac{\tau^{\ell + 1 - \lambda} S(\lambda)}{S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)}.
\end{equation*}

Similarly

\begin{equation*}
P(H_k = \mu^{(k)}, \forall k = 1, \ldots, \ell) = \prod_{k=1}^{\ell-1} m_{\mu^{(k+1)}, \kappa} \frac{\tau^{\ell - \mu} S(\lambda)}{S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)}.
\end{equation*}

This readily implies

\begin{equation*}
P(H_{\ell + 1} = \lambda | H_k = \mu^{(k)}, \forall k = 1, \ldots, \ell) = \frac{P(H_{\ell + 1} = \lambda, H_k = \mu^{(k)}, \forall k = 1, \ldots, \ell)}{P(H_k = \mu^{(k)}, \forall k = 1, \ldots, \ell)} = \frac{S(\lambda)}{S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)} \frac{\tau^{\ell - \mu} S(\lambda)}{S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)}.
\end{equation*}

\hfill \Box
5. Symmetrization

In subsection 4.1, we have chosen a probability distribution \( p \) on a crystal \( B(\pi_\kappa) \) where \( \kappa \in P_+ \) and \( \pi_\kappa \) is an elementary path from 0 to \( \kappa \) remaining in the cone \( \mathcal{C} \). This distribution depends on \( \tau \in \mathbb{R}^n_{\geq 0} \), and Proposition 4.1 gives a sufficient condition to ensure that \( S_\kappa(\tau) \) is finite. Since the characters of the highest weight representations are symmetric under the action of the Weyl group, it is possible to define, starting from the distribution \( p \) and for each \( w \) in the Weyl group \( \mathcal{W} \) of \( \mathfrak{g} \), a probability distribution \( p_w \) which reflects this symmetry.

5.1. Twisted probability distribution. Recall \( \tau = (\tau_1, \ldots, \tau_n) \in \mathcal{T} \) is fixed. Given any \( w \in \mathcal{W} \), we want to define a probability distribution on \( B(\kappa) \) for each \( w \in \mathcal{W} \). Recall that \( w(\alpha_i) \) is a (real) root of \( \mathfrak{g} \) for any \( w \in \mathcal{W} \) and any simple root \( \alpha_i \); this root is neither simple nor even positive in general. By general properties of the root systems, we know that \( w(\alpha_i) \) can be decomposed as

\[
w(\alpha_i) = \begin{cases} 
\alpha_{k_1} + \cdots + \alpha_{k_r} \\
-(\alpha_{k_1} + \cdots + \alpha_{k_r})
\end{cases}
\]

where \( \alpha_{k_1}, \ldots, \alpha_{k_r} \) are simple roots depending on \( w \). Let us define the \( n \)-tuple \( \tau^w = (\tau^w_1, \ldots, \tau^w_n) \in \mathbb{R}^n_{\geq 0} \) setting

\[
\tau^w_i = \begin{cases} 
\prod_{s=1}^i \tau_{k_s}^{-1} & \text{if } w(\alpha_i) = \alpha_{k_1} + \cdots + \alpha_{k_r}, \\
\prod_{s=1}^i \tau_{k_s} & \text{if } w(\alpha_i) = -(\alpha_{k_1} + \cdots + \alpha_{k_r}),
\end{cases}
\]

that is,

\[
(24) \quad \tau^w_i = \tau^{w(\alpha_i)}.
\]

More generally for any \( \bar{u} = u_1\alpha_1 + \cdots + u_n\alpha_n \in Q \), we have

\[
(\tau^w)^\bar{u} = (\tau^w_1)^{u_1} \cdots (\tau^w_n)^{u_n} = \tau^{w(\bar{u})}.
\]

Observe also that \( \tau^w \notin \mathcal{T} \) in general; indeed we have the following:

**Lemma 5.1.** \( \tau(w) \in \mathcal{T} \) if and only if \( w = 1 \).

**Proof.** It suffices to show that for any \( w \in \mathcal{W} \setminus \{Id\} \) distinct from the identity, there is at least a simple root \( \alpha_i \) such that \( w(\alpha_i) = -(\alpha_{k_1} + \cdots + \alpha_{k_r}) \in Q^+ \). Indeed, we will have in that case \( \tau^w_i = \frac{1}{\tau_{k_1} \cdots \tau_{k_r}} > 1 \) since \( \tau(w) \notin \mathcal{T} \). Consider \( w \in \mathcal{W} \setminus \{Id\} \) such that \( w(\alpha_i) \in Q^+ \) for any \( i = 1, \ldots, \ell \). Let us decompose \( w \) as a reduced word \( w = s_{i_1} \cdots s_{i_\ell} \). By Lemma 3.11 in [6], we must have \( w(\alpha_{i_\ell}) \in Q^- \), hence a contradiction. This means that \( w = 1 \). \( \square \)

Consider \( \kappa \in P_+ \). Recall that we have by definition \( s_\kappa = e^\kappa S_\kappa(T_1, \ldots, T_n) \) where \( T_i = e^{-\alpha_i} \). Since \( s_\kappa \) is symmetric under \( \mathcal{W} \), we have \( s_\kappa = e^{w(\kappa)} S_\kappa(T^w_1, \ldots, T^w_n) \) with \( T^w_i = e^{-w(\alpha_i)} \) for any \( i = 1, \ldots, n \). Therefore

\[
S_\kappa(T^w_1, \ldots, T^w_n) = e^{\kappa - w(\kappa)} S_\kappa(T_1, \ldots, T_n) \quad \text{for any } w \in \mathcal{W}.
\]

Since \( \kappa - w(\kappa) \) belongs to \( Q^+ \), we can specialize each \( T_i \) in \( \tau_i \). Then \( T^w_i \) is specialized in \( \tau^w_i \) and we get

\[
(25) \quad S_\kappa(\tau^w) = \tau^{w(\kappa) - \kappa} S_\kappa(\tau);
\]

in particular, it is finite.
Proof. (1) By definition of \( \bar{w} \), assume defined on \((B(\pi_k))^\otimes \ell \),
\[
 p^w_b := \frac{(\tau^w)^{\ell - wt(b)}}{S_{\ell}(\tau^w)^{\ell}} = \frac{\tau^{\ell w(\kappa) - wt(w(b))}}{S_{\ell}(\tau^w)^{\ell}}
\]
where \( w(b) \) is the image of \( b \) under the action of \( W \) (see assertion (6) of Theorem 3.6). In particular, \( p^1 = p \) coincides with the probability distribution (21).

The following lemma states that the probabilities \( p^w \) and \( p \) coincide up to the permutation of the elements in \( B(\pi_k)^{\otimes \ell} \) given by the action of \( w \) described in assertion (6) of Theorem 3.6.

**Lemma 5.3.** For any \( w \in \mathcal{W} \) and any \( b \in B(\pi_k)^{\otimes \ell} \), we have \( p^w_b = p_{w(b)} \), where \( w(b) \) is the image of \( b \) under the action of \( W \) (see assertion (6) of Theorem 3.6).

Proof. Recall that \( wt(w(b)) = w(wt(b)) \); therefore \( p_{w(b)} = \frac{\tau^{\ell w(\kappa) - wt(w(b))}}{S_{\ell}(\tau^w)^{\ell}}. \) On the other hand, by (25) we have \( p^w_b := \frac{\tau^{\ell w(\kappa) - wt(w(b))}}{S_{\ell}(\tau^w)^{\ell}} = \frac{\tau^{\ell w(\kappa) - wt(w(b))}}{S_{\ell}(\tau^w)^{\ell}} \), and the equality \( p^w_b = p_{w(b)} \) follows. \( \square \)

5.2. **Twisted random paths.** Let \( w \in \mathcal{W} \) and denote by \( X^w \) the random variable defined on \((B(\pi_k), p^w)\) with the law given by \[
\mathbb{P}(X^w = \pi) = p^w_\pi = p_{w(\pi)} \quad \text{for all} \quad \pi \in B(\pi_k).
\]
Set \( m^w := \mathbb{E}(X^w) \) and \( m := m^1 \).

**Proposition 5.4.** Assume \( \tau \in \mathcal{T} \). One gets

1. \( m(1) \in \mathcal{C} \),
2. \( m^w = w^{-1}(m) \),
3. \( m^w(1) \in \mathcal{C} \) if and only if \( w \) is equal to the identity.

Proof. (1) By definition of \( \mathcal{C} \), we have to prove that \( h_i(m(1)) > 0 \) for any \( i = 1, \ldots, n \). Recall that \( m = \sum_{\pi \in B(\pi_k)} p_\pi \pi; \) observe that the quantity
\[
c_i = h_i(m(1)) = \sum_{\pi \in B(\pi_k)} p_\pi h_i(\pi(1))
\]
is well defined by Corollary 4.5. We can decompose the crystal \( B(\pi_k) \) in its \( i \)-chains, that is, the sub-crystal obtained by deleting all the arrows \( j \neq i \). When \( \mathfrak{g} \) is not of finite type, the lengths of these \( i \)-chains are all finite but not bounded. The contribution to \( c_i \) of any \( i \)-chain \( C : a_0 \rightarrow a_1 \rightarrow \cdots \rightarrow a_k \) of length \( k \) is equal to \( c_i(C) = \sum_{j=0}^{k} p_{a_j} h_i(wt(a_j)) \). Since \( \bar{e}_i(a_0) = 0 \) and \( \bar{f}_i^{k+1}(a_0) = 0 \), we obtain \( h_i(wt(a_0)) = k \). By definition of the distribution \( p \) and Proposition 3.3, we have the relation \( p_{a_j} = \tau_i^j p_{a_0} \). Finally, we get
\[
c_i(C) = p_{a_0} \sum_{j=0}^{k} \tau_i^j (k - 2j) = p_{a_0} \sum_{j=0}^{[k/2]} (k - 2j)(\tau_i^j - \tau_i^{k-j}).
\]

In particular the hypothesis \( \tau_i \in [0,1[ \) for any \( i = 1, \ldots, n \) implies that \( c_i(C) > 0 \) for any \( i \)-chain of length \( k > 0 \); one thus gets \( c_i > 0 \) noticing that \( B(\pi_k) \) contains at
least an $i$-chain of length $k > 0$. Otherwise the action of the Chevalley generators $e_i, f_i$ on the irreducible module $V(\pi_\lambda)$ would be trivial.

(2) By Lemma 5.3 we can write

$$m^w = \sum_{\pi \in B(\pi_\kappa)} p_{w(\pi) \pi} = \sum_{\pi' \in B(\pi_\kappa)} p_{\pi'w^{-1}(\pi')} = w^{-1}\left(\sum_{\pi' \in B(\pi_\kappa)} p_{\pi' \pi'}\right) = w^{-1}(m)$$

where we use assertion (7) of Theorem 3.6 in the third equality.

(3) Since $m^w = w^{-1}(m)$ and $m(1) \in \hat{C}$, one gets $m^w(1) \notin C$ because $C$ is a fundamental domain for the action of the Weyl group $W$ on the Tits cone $\mathcal{X} = \bigcup_{w \in W} w(C)$ (see [6, Proposition 3.12]).

Now let $X^w = (X^w_\ell)_{\ell \geq 1}$ be a sequence of i.i.d. random variables defined on $B(\pi_\kappa)$ with probability distribution $p^w$. The random process $\mathcal{W}^w = (\mathcal{W}^w_\ell)_{\ell \geq 0}$ is defined by: for all $\ell \geq 1$ and $t \in [\ell - 1, \ell]$,

$$\mathcal{W}^w(t) := \Pi(\mathcal{W}^w)(t) = X^w_1 \otimes X^w_2 \otimes \cdots \otimes X^w_{\ell-1} \otimes X^w_{\ell}(t).$$

By (19), the random walk $W^w$ is defined as in subsection 2.3 from $\mathcal{W}^w$. For any $\ell \in \mathbb{Z}_{\geq 0}$, we also define the function $\psi^w_\ell$ on $P_+$ by setting

$$\psi^w_\ell(\mu) := \mathbb{P}_\mu(\mathcal{W}^w(t) \in C \text{ for any } t \in [0, \ell]).$$

The quantity $\psi^w_\ell(\mu)$ is equal to the probability of the event “$\mathcal{W}^w$ starting at $\mu$ remains in the cone $C$ until the instant $\ell$.” We also introduce the function

$$\psi^w(\mu) := \mathbb{P}_\mu(\mathcal{W}^w(t) \in C \text{ for any } t \geq 0).$$

For $w = 1$, we have $\psi = \psi^1$ (see (1)) and $\psi_\ell = \psi^1_\ell$.

The following proposition is a consequence of the previous lemma, Proposition 2.2 and Corollary 4.5

**Proposition 5.5.**

(1) We have $\lim_{\ell \to +\infty} \psi^w_\ell(\mu) = \psi^w(\mu)$ for any $\mu \in P_+$.

(2) If $w \neq 1$, then $\psi^w(\mu) = 0$ for any $\mu \in P_+$.

(3) If $w = 1$, then $\psi(\mu) \geq 0$ for any $\mu \in P_+$.

Similarly to Proposition 4.6 and using (25), we obtain

**Proposition 5.6.**

(1) For any weights $\beta$ and $\eta$, one gets

$$\mathbb{P}(W^w_{\ell+1} = \beta \mid W^w_\ell = \eta) = K_{\kappa,\beta-\eta}^{w(\kappa+\eta-\beta)} S^w_\kappa(\tau^w) = K_{\kappa,\beta-\eta}^{\tau^{-w(\kappa+\eta-\beta)}} S^w_\kappa(\tau) = K_{\kappa,\beta-\eta}^{\tau^{-w(\kappa+\beta-\eta)}} S^w_\kappa(\tau).$$

(2) For any dominant weights $\lambda$ and $\mu$, one gets

$$\mathbb{P}(W^w_{\ell} = \lambda, W^w_0 = \mu, W^w(t) \in C \text{ for any } t \in [0, \ell]) = f^\ell_{\lambda/\mu} S^w_\kappa(\tau^w) = f^\ell_{\lambda/\mu} S^w_\kappa(\tau).$$

In particular,

$$\mathbb{P}(W^w_{\ell+1} = \lambda, W^w_{\ell} = \mu, W^w(t) \in C \text{ for any } t \in [\ell, \ell + 1]) = m^{\lambda}_{\mu,\kappa} S^w_\kappa(\tau) = m^{\lambda}_{\mu,\kappa} S^w_\kappa(\tau).$$
6. Law of the conditioned random path

6.1. The harmonic function $\psi$. By assertion (2) of the previous proposition, we can write

$$\psi^w_\ell(\mu) = \mathbb{P}_\mu(W^w(t) \in C \text{ for any } t \in [0, \ell]) = \sum_{\lambda \in P_+} f^\ell_{\lambda/\mu} \frac{\tau^{\ell \lambda + w(\mu) - w(\lambda)}}{S_\lambda(\tau)^\ell}$$

where $f^\ell_{\lambda/\mu}$ is the number of highest weight vertices in the crystal $B(\mu) \otimes B(\kappa) \cong \bigoplus_{\lambda \in P_+} B(\lambda)^{\otimes f^\ell_{\lambda/\mu}}$.

By interpreting (27) in terms of characters, we get

$$\psi^w_\ell(\mu) \prod_{\alpha \in R_+} (1 - e^{-\alpha})^{m_\alpha} s_\mu \otimes s^\ell_\mu = \sum_{\lambda \in P_+} f^\ell_{\lambda/\mu} \sum_{w \in W} \varepsilon(w) e^{w(\lambda + \rho) - \rho}.$$ 

In the previous formal series in $\mathbb{C}[[P]]$, all the monomials $e^{w(\lambda + \rho) - \rho}$ with $w \in W$ and $\lambda \in P_+$ are distinct (see [6, Proposition 3.12]). We thus also have

$$\prod_{\alpha \in R_+} (1 - e^{-\alpha})^{m_\alpha} S_\mu \otimes S^\ell_\mu = \sum_{w \in W} \varepsilon(w) \sum_{\lambda \in P_+} f^\ell_{\lambda/\mu} e^{w(\lambda + \rho) - \rho}$$

or equivalently

$$\prod_{\alpha \in R_+} (1 - e^{-\alpha})^{m_\alpha} S_\mu \otimes S^\ell_\mu = \sum_{w \in W} \varepsilon(w) \sum_{\lambda \in P_+} f^\ell_{\lambda/\mu} e^{w(\lambda + \rho) - \rho - \ell \kappa - \mu}.$$ 

We now need the following lemma.

**Lemma 6.1.** For any $w \in W$ and $\mu \in P_+$, set $\Pi^w_\ell(\mu) := \sum_{\lambda \in P_+} f^\ell_{\lambda/\mu} \frac{\tau^{\ell \lambda + w(\mu) - w(\lambda)}}{S_\lambda(\tau)^\ell}$. We then have $\lim_{\ell \to +\infty} \Pi^w_\ell(\mu) = 0$ when $w \neq 1$ and the series $\sum_{w \in W} \varepsilon(w) \Pi^w_\ell(\mu)$ converges uniformly in $\ell$.

*Proof.* Using (26), one gets

$$\Pi^w_\ell(\mu) = \tau^{\rho - w(\rho) + \mu - w(\mu)} \sum_{\lambda \in P_+} f^\ell_{\lambda/\mu} \frac{\tau^{\ell \lambda + w(\mu) - w(\lambda)}}{S_\lambda(\tau)^\ell} = \tau^{\rho - w(\rho) + \mu - w(\mu)} \psi^w_\ell(\mu).$$

Fix $w \neq 1$. Since $\tau^{\rho - w(\rho) + \mu - w(\mu)}$ does not depend on $\ell$ and $\lim_{\ell \to +\infty} \psi^w_\ell(\mu) = 0$ by Proposition 5.5, we derive $\lim_{\ell \to +\infty} \Pi^w_\ell(\mu) = 0$ as desired.

Now, we obviously have $0 \leq \psi^w_\ell(\mu) \leq 1$, and the series $\sum_{w \in W} \tau^{\rho - w(\rho) + \mu - w(\mu)}$ converges by Corollary 4.3. The uniform convergence in $\ell$ of the series $\sum_{w \in W} \varepsilon(w) \Pi^w_\ell(\mu)$ thus follows from the inequality $|\varepsilon(w) \Pi^w_\ell(\mu)| \leq \tau^{\rho - w(\rho) + \mu - w(\mu)}$, which is a direct consequence of (30). \square
We can now set $\tau_i = e^{-\alpha_i}$ in (29) and get

$$
\prod_{\alpha \in R_+} (1 - \tau^\alpha)^{m_\alpha} S_{\mu}(\tau) = \sum_{w \in W} \varepsilon(w) \sum_{\lambda \in P_+} f_{\lambda/\mu}^{\tau} S_{\mu}(\tau). \frac{\tau^{\ell \kappa + \rho + \mu - w(\lambda + \rho)}}{S_{\kappa}(\tau)^{\ell}}.
$$

Consequently, we have

$$
\prod_{\alpha \in R_+} (1 - \tau^\alpha)^{m_\alpha} S_{\mu}(\tau) = \sum_{w \in W} \varepsilon(w) \Pi^w_\ell (\mu) = \Pi^1_\ell (\mu) + \sum_{w \neq 1} \varepsilon(w) \Pi^w_\ell (\mu)
$$

with $\Pi^1_\ell (\mu) = \psi_\ell (\mu)$ by (30). Letting $\ell \to +\infty$, the previous lemma finally gives

$$
\psi(\mu) = \prod_{\alpha \in R_+} (1 - \tau^\alpha)^{m_\alpha} S_{\mu}(\tau).
$$

We have established the following theorem, which is the analogue in our context of Corollary 7.4.3 in [10]. This is in fact the central result of the paper. Recall we have for any $\pi \in P_+$, $\psi(\mu) = \mathbb{P}_\mu (W(t) \in \mathcal{C} \text{ for any } t \geq 0)$.

**Theorem 6.2.** For any $\mu \in P_+$, we have

$$
\psi(\mu) = \prod_{\alpha \in R_+} (1 - \tau^\alpha)^{m_\alpha} S_{\mu}(\tau) > 0.
$$

In particular, the harmonic function $\psi$ is positive and does not depend on the dominant weight $\kappa$ considered.

We can now extend the main results of [10] and [15] to the case of random walks defined from nonminuscule representations.

**Corollary 6.3.** The law of the random walk $W$ conditioned by the event

$$
E := (W(t) \in \mathcal{C} \text{ for any } t \geq 0)
$$

is the same as the law of the Markov chain $H$ defined as the generalized Pitman transform of $W$ (see Theorem 4.7). In particular, this law depends only on $\kappa$ and not on the choice of the path $\pi_\kappa$ such that $\text{Im} \pi_\kappa \subset \mathcal{C}$.

**Proof.** Let $\Pi$ be the transition matrix of $W$ and $\Pi^E$ its restriction to the event $E$. We have seen in subsection 2.1 that the transition matrix of $W$ conditioned by $E$ is the $h$-transform of $\Pi^E$ by the harmonic function

$$
h_E(\mu) := \mathbb{P}_\mu (W(t) \in \mathcal{C} \text{ for any } t \geq 0).
$$

By the previous theorem, we have $h_E = \psi$. It also easily follows from Theorem 4.7 and the expression we have just obtained for the harmonic function $\psi$ that the transition matrix of $H$ is the $\psi$-transform of $\Pi^E$. Therefore both $H$ and the conditioning of $W$ by $E$ have the same law. \qed

### 6.2. Random walks defined from nonirreducible representations.

For simplicity we restrict ourselves in this paragraph to the case where $\mathfrak{g}$ is a (finite-dimensional) Lie algebra with (invertible) Cartan matrix $A$. In particular, $m_\alpha = 1$ for any $\alpha \in R_+$. Consider $\tau = (\tau_1, \ldots, \tau_n) \in T$. Then both root and weight lattices have the same rank $n$. Moreover, the Cartan matrix $A$ is the transition matrix between the weight and root lattices. In particular, each weight $\beta \in P$ decomposes on the basis of simple roots as $\beta = \beta'_1 \alpha_1 + \cdots + \beta'_n \alpha_n$ where $(\beta'_1, \ldots, \beta'_n) \in \frac{1}{\det A} \mathbb{Z}^n$, and we can set $\tau^\beta = \tau^\beta_1 \tau^\beta_2 \cdots \tau^\beta_n$. 

Let $M$ be a finite-dimensional $\mathfrak{g}$-module with decomposition in irreducible components

$$M \simeq \bigoplus_{\kappa \in \mathcal{X}} V(\kappa)^{\oplus a_\kappa}$$

where $\mathcal{X}$ is a finite subset of $P_+$ and $a_\kappa > 0$ for any $\kappa \in \mathcal{X}$. For each $\kappa \in \mathcal{X}$ choose a path $\eta_\kappa$ in $P$ from 0 to $\kappa$ contained in $\mathcal{C}$. Let $B(\mathcal{X})$ be the set of paths obtained by applying the operators $\hat{e}_i, \hat{f}_i$, $i = 1, \ldots, n$ to the paths $\eta_\kappa, \kappa \in \mathcal{X}$. This set is a realization of the crystal of the $\mathfrak{g}$-module $\bigoplus_{\kappa \in \mathcal{X}} V(\kappa)$ (without multiplicities), and we have

$$B(\mathcal{X}) = \bigcup_{\kappa \in \mathcal{X}} B(\eta_\kappa).$$

Given $\pi = \pi_1 \otimes \cdots \otimes \pi_\ell$ in $B^{\otimes \ell}(\mathcal{X})$ such that $\pi_a \in B(\kappa_a)$ for any $a = 1, \ldots, \ell$, we set $a_\pi = a_{\kappa_1} \cdots a_{\kappa_\ell}$. By formulas (12), the function $a_\pi$ is constant on the connected components of $B^{\otimes \ell}(\mathcal{X})$.

We are going to define a probability distribution on $B(\mathcal{X})$ compatible with its weight graduation and taking into account the multiplicities $a_\kappa$. We cannot proceed as in (21) by working only with the root lattice of $\mathfrak{g}$ since $B(\mathcal{X})$ contains fewer highest weight paths. So the underlying lattice to consider is the weight lattice. We first set

$$\Sigma_M(\tau) = \sum_{\kappa \in \mathcal{X}} \sum_{\pi \in B(\eta_\kappa)} a_\kappa \tau^{-\text{wt}(\pi)} = \sum_{\pi \in B(\mathcal{X})} a_\pi \tau^{-\text{wt}(\pi)}$$

$$= \sum_{\kappa \in \mathcal{X}} a_\kappa \tau_\kappa(\tau) = \sum_{\kappa \in \mathcal{X}} a_\kappa \tau^{-\kappa}\tau(\tau).$$

We define the probability distribution $p$ on $B(\mathcal{X})$ by setting $p_\pi = a_\pi \tau^{-\text{wt}(\pi)} \Sigma_M(\tau)$ for any $\pi \in B(\eta_\kappa)$. When $\text{card}(\mathcal{X}) = 1$, we recover the probability distribution of subsection 4.1. Observe that we have

$$\Sigma_M(\tau^\ell) = \sum_{\pi \in B^{\otimes \ell}(\mathcal{X})} a_\pi \tau^{-\text{wt}(\pi)}$$

for any $\ell \geq 0$.

So we can define a probability distribution $p^{\otimes \ell}$ on $B^{\otimes \ell}(\mathcal{X})$ such that

$$p_\pi = a_\pi \tau^{-\text{wt}(\pi)} \Sigma_M(\tau)^\ell$$

for any $\pi = \pi_1 \otimes \cdots \otimes \pi_\ell \in B^{\otimes \ell}(\mathcal{X})$.

Let $X = (X_\ell)_{\ell \geq 1}$ be a sequence of i.i.d. random variables defined on $B(\mathcal{X})$ with probability distribution $p$. The random process $\mathcal{W}$ and the random walk $W$ are then defined from $X$ and $p^{\otimes \mathbb{N}}$ as in subsection 2.3.

It is then possible to extend our results to the random path $\mathcal{W}$ and its corresponding random walk $W$ obtained from the set of elementary paths $B(\mathcal{X})$. We then have

$$\mathbb{P}(W_{\ell+1} = \beta \mid W_\ell = \gamma) = \frac{K_{M,\beta-\gamma}}{\Sigma_M(\tau)^\ell}$$

for any weights $\beta$ and $\gamma$ where $K_{M,\beta-\gamma}$ is the dimension of the space of weight $\beta - \gamma$ in $M$. We indeed have $K_{M,\beta-\gamma} = \sum_{\kappa \in \mathcal{X}} a_\kappa K_{\kappa,\beta-\gamma}$ where $K_{\kappa,\beta-\gamma}$ is the number of paths $\eta \in B(\kappa)$ such that $\eta(1) = \beta - \gamma$. Given two dominant weights $\lambda$ and $\mu$, we also get

$$\mathbb{P}(W_{t+1} = \lambda \mid W_t = \mu, \mathcal{W}(t) \in \mathcal{C} \text{ for any } t \in [\ell, \ell+1]) = \frac{m_{M,\mu,\lambda}^\ell}{\Sigma_M(\tau)^\ell}$$
where \( m_{\lambda M,\mu}^\lambda \) is the multiplicity of \( V(\lambda) \) in \( M \otimes V(\mu) \). We indeed have \( m_{\lambda M,\mu}^\lambda = \sum_{\eta \in \mathcal{M}} a_\eta m_{\lambda,\mu}^\eta \), where \( m_{\lambda,\mu}^\eta \) is the number of paths \( \eta \in B(\kappa) \) such that \( \eta(1) = \lambda - \mu \) which remains in \( \mathcal{C} \).

We define the generalized Pitman transform \( \mathcal{P} \) and the Markov chain \( H \) as in subsection 4.3. For any \( \ell \geq 1 \), we write \( \psi_\ell(\mu) = \mathbb{P}_\mu(\mathcal{W}(t) \in \mathcal{C} \text{ for any } t \in [1, \ell]) \). We then have

\[
\psi_\ell(\mu) = \sum_{\pi \in B^{\otimes \ell}(\mathcal{C}), \mu + \pi(t) \in \mathcal{C} \text{ for } t \in [0, \ell]} p_\pi,
\]

where \( p_\pi = \sum_{\lambda \in P_+} \pi(\lambda) \sum_{\mu \in B^{\otimes \ell}(\mathcal{C}), \mu + \pi(t) \in \mathcal{C} \text{ for } t \in [0, \ell], \pi(t) = \lambda} a_\pi \frac{\tau^{\mu - \lambda}}{\sum_{\tau} m_{\lambda M,\mu}^\tau \tau^{\mu - \lambda}} \), where \( f_{\lambda/\mu}^\ell = \sum_{\pi \in B^{\otimes \ell}(\mathcal{C}), \mu + \pi(t) \in \mathcal{C} \text{ for } t \in [0, \ell], \pi(t) = \lambda} a_\pi \) by an easy extension of assertion (10) in Theorem 6.4. We can now establish the following theorem.

**Theorem 6.4.** The law of the random walk \( \mathcal{W} \) conditioned by the event

\( E := (\mathcal{W}(t) \in \mathcal{C} \text{ for any } t \geq 0) \)

is the same as the law of the Markov chain \( H \) defined as the generalized Pitman transform of \( \mathcal{W} \) (see Theorem 4.7). The associated transition matrix \( \Pi^E \) verifies

\[
\Pi^E(\mu, \lambda) = \frac{S_\lambda(\tau)}{S_\mu(\tau) \sum_{\tau} m_{\lambda M,\mu}^\tau \tau^{\mu - \lambda}},
\]

and we have

\[
\mathbb{P}_\mu(\mathcal{W}(t) \in \mathcal{C} \text{ for any } t \geq 0) = \prod_{\alpha \in R^+} (1 - \tau^\alpha) S_\mu(\tau).
\]

**Proof.** The computation of the harmonic function \( \psi(\mu) = \mathbb{P}_\mu(\mathcal{W}(t) \in \mathcal{C} \text{ for any } t \geq 0) \) is similar to subsection 6.1. We have from the Weyl character formula

\[
\prod_{\alpha \in R^+} (1 - e^{-\alpha}) e^{-\mu} s_\mu = \sum_{\lambda \in P_+} f_{\lambda/\mu}^\ell \sum_{\omega \in \mathcal{W}} \varepsilon(\omega) \frac{e^{\omega(\lambda + \rho) - \rho - \mu}}{s_M^\ell},
\]

where \( s_M = \text{char}(M) \). When we specialize \( \tau_i = e^{\alpha_i} \) in \( s_M \), we obtain \( \Sigma_M(\tau) \). Hence

\[
\prod_{\alpha \in R^+} (1 - \tau^\alpha) S_\mu(\tau) = \sum_{\lambda \in P_+} f_{\lambda/\mu}^\ell \sum_{\omega \in \mathcal{W}} \varepsilon(\omega) \frac{\tau^{\mu + \rho - w(\lambda + \rho)}}{\sum_{\tau} \tau^{\mu + \rho - w(\lambda + \rho)}}.
\]

If we set \( \Pi^w_\ell(\mu) := \sum_{\lambda \in P_+} f_{\lambda/\mu}^\ell \frac{\tau^{\rho + \mu - w(\lambda + \rho)}}{\sum_{\tau} \tau^{\mu + \rho - w(\lambda + \rho)}} \), we yet obtain \( \lim_{\ell \to +\infty} \Pi^w_\ell(\mu) = 0 \) when \( w \neq 1 \) and \( \Pi^w_1(\mu) = \psi_\ell(\mu) \). Moreover

\[
\prod_{\alpha \in R^+} (1 - \tau^\alpha) S_\mu(\tau) = \sum_{w \in \mathcal{W}} \varepsilon(\omega) \Pi^w_\ell(\mu) = \Pi^w_1(\mu) + \sum_{w \neq 1} \varepsilon(\omega) \Pi^w_\ell(\mu)
\]

so the harmonic function \( \psi = \lim_{\ell \to +\infty} \psi_\ell \) is also given by

\[
\psi(\mu) = \prod_{\alpha \in R^+} (1 - \tau^\alpha) S_\mu(\tau).
\]

Since \( \Pi^E \) is the Doob \( \psi \)-transform of the restriction of \( \mathcal{W} \) to \( \mathcal{C} \), we obtain the desired expression for \( \Pi^E(\mu, \lambda) \).
To see that $\Pi^E$ coincides with the law of the image of $W$ under the generalized Pitman transform, we proceed as in the proof of Theorem 4.7. Consider $\mu = \mu^{(\ell)}, \mu^{(\ell-1)}, \ldots, \mu^{(1)}$ a sequence of elements in $P_+$. Let $S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)$ be the set of paths $b^h \in B^{\otimes \ell}(x)$ remaining in $C$ and such that $b^h(k) = \mu^{(k)}$, $k = 1, \ldots, \ell$ and $b^{(\ell+1)} = \lambda$. Consider $b = b_1 \otimes \cdots \otimes b_\ell \otimes b_{\ell+1} \in B^{\otimes \ell+1}(x)$. We have $P(b_1 \otimes \cdots \otimes b_\ell)(k) = \mu^{(k)}$ for any $k = 1, \ldots, \ell$ and $P(b)(\ell + 1) = \lambda$ if and only if $P(b) \in S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)$. Moreover, by (21), for any $b^h \in S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)$, we have

$$\mathbb{P}(b \in B(b^h)) = \sum_{b \in B(b^h)} p_b = \sum_{b \in B(b^h)} a_b \frac{\tau^{-\lambda} S_\lambda(\tau)}{\sum_{M(\tau)}^{\ell+1}} = a_{b^h} \frac{\tau^{-\lambda} S_\lambda(\tau)}{\sum_{M(\tau)}^{\ell+1}}$$

since $a_b = a_{b^h}$ for any $b \in B(b^h)$. This gives

$$\mathbb{P}(H_{\ell+1} = \lambda, H_k = \mu^{(k)}, \forall k = 1, \ldots, \ell) = \frac{\tau^{-\lambda} S_\lambda(\tau)}{\sum_{M(\tau)}^{\ell+1}} \sum_{b^h \in S(\mu^{(1)}, \ldots, \mu^{(\ell)}, \lambda)} a_{b^h} \prod_{k=1}^{\ell-1} m_{\mu^{(k+1)}, M} \times m_{\mu, M}$$

also using an extension of assertion (10) in Theorem 3.6. Similarly

$$\mathbb{P}(H_k = \mu^{(k)}, \forall k = 1, \ldots, \ell) = \frac{\tau^{-\mu} S_\mu(\tau)}{\sum_{M(\tau)}^{\ell}} \prod_{k=1}^{\ell-1} m_{\mu^{(k+1)}, M},$$

which implies

$$\mathbb{P}(H_{\ell+1} = \lambda \mid H_k = \mu^{(k)}, \forall k = 1, \ldots, \ell) = \frac{S_\lambda(\tau)}{S_\mu(\tau) \sum_{M(\tau)}^{\ell+1}} m_{\mu, \lambda} \tau^{\mu - \lambda}.$$

\[ \square \]

6.3. Example: Random walk to the height closest neighbors. We now study in detail the case of the random walk in the plane with transitions 0 and the height closest neighbors. The underlying representation is not irreducible and does not decompose as a sum of minuscule representations. So the conditioning of this walk cannot be obtained by the methods of [10].

The root system of type $C_2$ is realized in $\mathbb{R}^2 = \mathbb{R} \varepsilon_1 \oplus \mathbb{R} \varepsilon_2$. The Cartan matrix is

$$A = \begin{pmatrix} 2 & -1 \\ -2 & 2 \end{pmatrix}. $$

The simple roots are then $\alpha_1 = \varepsilon_1 - \varepsilon_2$ and $\alpha_2 = 2 \varepsilon_2$. We have $P = \mathbb{Z}^2$. The fundamental weights are $\omega_1 = \varepsilon_1$ and $\omega_2 = \varepsilon_1 + \varepsilon_2$. We have $C = \{(x, y) \in \mathbb{R}^2 \mid x \geq y \geq 0\}$ and $P_+ = \{\lambda = (\lambda_1, \lambda_2) \mid \lambda_1 \geq \lambda_2 \geq 0\}$, the set of partitions with two parts. Choose $\tau_1 \in [0, 1], \tau_2 \in [0, 1]$. For $\lambda = (\lambda_1, \lambda_2) \in P_+$, we have $\lambda = \lambda_1 \alpha_1 + \frac{\lambda_1 + \lambda_2}{2} \alpha_2$. Thus $\tau^\lambda = \tau_1^{\lambda_1} (\sqrt{2})^{\lambda_1 + \lambda_2}$.

Consider the $\mathfrak{sp}_4(\mathbb{C})$-module $M = V(1)^{\otimes a_1} \oplus V(1, 1)^{\otimes a_2}$. The elementary paths in $B(\varepsilon)$ can be easily described from the highest weight paths

$$\pi_1 : t \mapsto t \varepsilon_1$$

and $\gamma_1 \gamma_2 : \begin{cases} 2t \varepsilon_1, t \in [0, \frac{1}{2}] \\ \varepsilon_1 + 2(t - \frac{1}{2}) \varepsilon_2, t \in [\frac{1}{2}, 1] \end{cases}$ in $C$.\[ \square \]

\[ \text{2The results of } [10] \text{ permit us nevertheless to study the random walk in the space } \mathbb{R}^3 \text{ with transitions } \pm \varepsilon_1 \pm \varepsilon_2 \pm \varepsilon_3 \text{ corresponding to the weights of the spin representation of } g = \mathfrak{so}_9. \]
We obtain $B(\pi) = B(\pi_1) \oplus B(\gamma_{12})$ where

1. $B(\pi_1): \pi_1 : t \mapsto t \varepsilon_1, \pi_2 : t \mapsto t \varepsilon_2, \pi_T : t \mapsto -t \varepsilon_1$ and $\pi_2 : t \mapsto -t \varepsilon_2$ with $t \in [0,1]$.
2. $B(\gamma_{12})$:

\[ \gamma_{12} : \begin{cases} 2t \varepsilon_1, t \in [0, \frac{1}{2}] \\ \varepsilon_1 + 2(t - \frac{1}{2}) \varepsilon_2, t \in [\frac{1}{2}, 1] \end{cases} \]

\[ \gamma_{12} : \begin{cases} 2t \varepsilon_2, t \in [0, \frac{1}{2}] \\ \varepsilon_2 - 2(t - \frac{1}{2}) \varepsilon_2, t \in [\frac{1}{2}, 1] \end{cases} \]

\[ \gamma_{2T} : \begin{cases} 2t \varepsilon_2, t \in [0, \frac{1}{2}] \\ \varepsilon_2 - 2(t - \frac{1}{2}) \varepsilon_2, t \in [\frac{1}{2}, 1] \end{cases} \]

The set of positive roots is

\[ \{ \tau \in \mathbb{Z}^2 : \tau \geq \tau_1 + \tau_2 + \tau_1^2 \} \]

Moreover, the law of the random walk $W(t)$ is the union of the two following crystals:

\[ \pi_1 \rightarrow \pi_2 \rightarrow \pi_2 \rightarrow \pi_1 \rightarrow \pi_T, \]

\[ \gamma_{12} \rightarrow \gamma_{12} \rightarrow \gamma_{2T} \rightarrow \gamma_{2T} \rightarrow \gamma_{2T}. \]

Observe that for the path $\gamma_{2T}$, we have $\gamma_{2T}(0) = \gamma_{2T}(1) = 0$. The other transitions correspond to the 8 closest neighbors in the lattice $\mathbb{Z}^2$.

We now define the probability distribution $p$ on the set $B(\pi_1) \oplus B(\gamma_{12}) \oplus \gamma_{2T}$. We have

\[ \Sigma M(\tau) = a_1 \frac{1 + \tau_1 + \tau_1 \tau_2 + \tau_1^2 \tau_2}{\tau_1 \sqrt{\tau_2}} + a_2 \frac{1 + \tau_2 + \tau_1 \tau_2 + \tau_2^2 \tau_1 + \tau_1^2 \tau_2}{\tau_1 \tau_2}. \]

The probability $p$ is defined by

\[ p_1 = \frac{a_1}{\Sigma M(\tau) \tau_1 \sqrt{\tau_2}}, \quad p_2 = \frac{a_1}{\Sigma M(\tau) \sqrt{\tau_2}}, \quad p_T = \frac{a_1 \tau_1 \sqrt{\tau_2}}{\Sigma M(\tau)}, \]

\[ p_{12} = \frac{a_2}{\Sigma M(\tau) \tau_1 \tau_2}, \quad p_{12} = \frac{a_2}{\Sigma M(\tau) \tau_1}, \quad p_{2T} = \frac{a_2 \tau_1}{\Sigma M(\tau)}, \quad p_{2T} = \frac{a_2 \tau_1 \tau_2}{\Sigma M(\tau)}. \]

The set of positive roots is

\[ R_+ = \{ \varepsilon_1 \pm \varepsilon_2, 2\varepsilon_1, 2\varepsilon_2 \} \] and $\rho = (2, 1)$.

The action of the Weyl group on $\mathbb{Z}^2$ yields the 8 transformations which preserves the square of vertices ($\pm 1, \pm 1$). For any partition $\mu = (\mu_1, \mu_2) \in P_+$, we obtain by the Weyl character formula and Theorem 6.2

\[ \psi(\mu) = \mathbb{P}_\mu(W(t) \in \mathcal{C}, t \geq 0) = (1 - \tau_1)(1 - \tau_2)(1 - \tau_1 \tau_2)(1 - \tau_1^2 \tau_2)S_\mu(\tau_1, \tau_2) \]

\[ = \sum_{\mu \in \mathcal{W}} \varepsilon(w) \tau^{\mu - \mu(\mu + \rho) - \mu(\mu - \rho)} \]

\[ = 1 + \tau_1^\mu_1 \mu_2 + \tau_2^\mu_2 \mu_1 + \tau_1 \tau_2^\mu_1 + \mu_2 + 3 \tau_1^\mu_1 + \mu_2 + 3 \mu_2 + 1 \]

\[ - \tau_1^\mu_1 \mu_2 + 1 - \tau_2^\mu_2 + 1 - \tau_1^\mu_1 + 4 \tau_2^\mu_2 + 1 - \tau_1^\mu_1 + \mu_2 + 3 \tau_2^\mu_1 + \mu_2 + 3. \]

Moreover, the law of the random walk $W$ conditioned by the event

\[ E := (W(t) \in \mathcal{C} \text{ for any } t \geq 0) \]

is the same as the law of the Markov chain $H$ defined as the generalized Pitman transform of $W$ (see Theorem 4.7). To compute the associated transition matrix
$M$, we need the tensor product multiplicities $m_{\mu,M}^\lambda = a_1 m_{(1,0),\mu}^\lambda + a_2 m_{(1,1),\mu}^\lambda$. We have for any partitions $\lambda$ and $\mu$ two parts:

$$m_{(1,0),\mu}^\lambda = \begin{cases} 1 & \text{if } \lambda \text{ and } \mu \text{ are equal or differ by only one box} \\ 0 & \text{otherwise} \end{cases}$$

and

$$m_{(1,1),\mu}^\lambda = \begin{cases} 1 & \text{if } \lambda \text{ and } \mu \text{ are equal or differ by two boxes in different rows} \\ 0 & \text{otherwise.} \end{cases}$$

We thus have for any $\lambda, \mu \in P_+$,

$$\Pi^E(\mu, \lambda) = \frac{\psi(\lambda)}{\psi(\mu)\sum_M(\tau)} \left(a_1 m_{(1,0),\mu}^\lambda + a_2 m_{(1,1),\mu}^\lambda\right) \tau_1^{\mu_1 - \lambda_1} \sqrt{\tau_2^{(\mu_1 + \mu_2 - \lambda_1 - \lambda_2)}}.$$

7. Some consequences

In the remaining of the paper, we assume that $g$ is of finite type and $W$ is constructed from an irreducible $\mathfrak{g}$-module $V(\kappa)$ in the category $O_{int}$. Then the crystal $B(\pi_\kappa)$ has a finite number of paths which all have the same length as $\pi_\kappa$ since $W$ contains only isometries.

7.1. Asymptotics for the multiplicities $f_{\lambda/\mu}^\ell$. We will use later a quotient version of a local limit theorem for these random paths; following [10], we may state

**Proposition 7.1.** Let $(g_\ell), (h_\ell)$ be two sequences in $P$ such that the events $(W_\ell = g_\ell)$ and $(W_\ell = g_\ell + h_\ell)$ have nonzero probability for $\ell > 0$ large enough. Assume there exists $\alpha < 2/3$ such that $\lim \ell^{-\alpha} \|g_\ell - \ell m\| = 0$ and $\lim \ell^{-1/2} \|h_\ell\| = 0$. Then, when $\ell$ tends to infinity, one gets

$$\mathbb{P}_0(W_\ell = g_\ell + h_\ell, W(t) \in C \text{ for any } t \in [0, \ell]) \sim \mathbb{P}_0(W_\ell = g_\ell, W(t) \in C \text{ for any } t \in [0, \ell]).$$

**Proof.** The proof of this statement follows line by line the one of Theorem 4.3 in [10]. Without loss of generality, we may assume that the law of the $X_\ell$ is aperiodic in $P$, which means that its support generates $P$ and is not included in a coset of a proper subgroup of $P$: this readily implies that $\mathbb{P}_0(W_\ell = g_\ell) > 0$ and $\mathbb{P}_0(W_\ell = g_\ell + h_\ell) > 0$ for when $(g_\ell)_\ell$ and $(h_\ell)_\ell$ satisfy the conditions of the proposition and $\ell$ large enough.

When the law of the $X_\ell$ is not aperiodic, the random walk $(W_\ell)_\ell$ has a finite number $p$ of periodic classes and the condition $\mathbb{P}_0(W_\ell = g_\ell) > 0$ and $\mathbb{P}_0(W_\ell = g_\ell + h_\ell) > 0$ corresponds to the fact that $g_\ell$ and $g_\ell + h_\ell$ belong to the same periodic class indexed by the value of $\ell$ modulo $p$; the statement in this case follows from the one in the aperiodic one by induction of the random walk on each periodic class.

We fix a real number $\beta$ such that $\frac{1}{2} < \alpha < \beta < \frac{2}{3}$, set $b_\ell = [\ell^\beta]$ and choose $\delta > 0$ such that $B_\ell := := B(m, \delta) \subset C$.

As in [10], we first check that

$$\mathbb{P}_0(W_\ell = g_\ell, W(t) \in C \text{ for any } t \in [0, \ell]) \mathbb{P}_0(W_\ell = g_\ell, W_{b_\ell} \in B_{b_\ell}, W(t) \in C \text{ for any } t \in [0, b_\ell]) \rightarrow 1;$$

in others words, one may “forget” the conditioning $(W(t) \in C \text{ for any } t \in [b_\ell, \ell])$ in the event $(W_\ell = g_\ell, W(t) \in C \text{ for any } t \in [0, \ell])$. The same result holds if one replaces $g_\ell$ by $g_\ell + h_\ell$ for $\lim \ell^{-\alpha} \|g_\ell + h_\ell - \ell m\| = 0$.
To achieve the proof of the proposition, it now suffices to establish that
\[
\frac{\mathbb{P}_0(W_\ell = g_\ell + h_\ell, W_{b_\ell} \in B_{b_\ell}, W(t) \in C \text{ for any } t \in [0, b_\ell])}{\mathbb{P}_0(W_\ell = g_\ell, W_{b_\ell} \in B_{b_\ell}, W(t) \in C \text{ for any } t \in [0, b_\ell])} \to 1.
\]
Since the increments of the random walk \((W_\ell)_\ell\) are independent with the same law, we may write
\[
\mathbb{P}_0(W_\ell = g_\ell, W_{b_\ell} \in B_{b_\ell}, W(t) \in C \text{ for any } t \in [0, b_\ell])
= \sum_{x \in B_{b_\ell} \cap P_+} \mathbb{P}_0(W_{\ell - b_\ell} = g_\ell - x) \times \mathbb{P}_0(W_\ell = x, W(t) \in C \text{ for any } t \in [0, b_\ell]).
\]
This leads to the proposition since \(\mathbb{P}_0(W_{\ell - b_\ell} = g_\ell - x) \sim \mathbb{P}_0(W_{\ell - b_\ell} = g_\ell + h_\ell - x)\) uniformly in \(x \in B_{b_\ell}\).

Consider \(\lambda, \mu \in P_+\) and \(\ell \geq 1\) such that \(f^\ell_{\lambda, \mu} > 0\) and \(f^\ell_{\lambda} > 0\). Then, we must have \(\ell \kappa + \mu - \lambda \in Q_+\) and \(\ell \kappa - \lambda \in Q_+\). Therefore \(\mu \in Q\) and it decomposes as a sum of simple roots. In the sequel, we will assume the condition \(\mu \in Q \cap P_+\) is satisfied.

We assume the notation and hypotheses of Theorem 6.2. Consider a sequence \(\lambda^{(\ell)}\) of dominant weights such that \(\lambda^{(\ell)} = \ell m(1) + o(\ell)\). Following Proposition 5.3 in [10], one gets the following decomposition:
\[
\frac{f^\ell_{\lambda^{(\ell)}}, \mu}{f^\ell_{\lambda^{(\ell)}}} = \sum_{\gamma \in P} K_{\mu, \gamma} \frac{f^{\ell}_{\lambda^{(\ell)}}, \gamma}{f^{\ell}_{\lambda^{(\ell)}}} = \tau^{-\mu} \sum_{\gamma \in P} K_{\mu, \gamma} \frac{f^{\ell}_{\lambda^{(\ell)}}, -\gamma}{f^{\ell}_{\lambda^{(\ell)}}} \tau^{-\lambda^{(\ell)} + \gamma}
\]
where the sums are finite since the set of weights in \(V(\mu)\) is finite. By assertion (2) of Proposition 4.6 we have, for any \(\gamma \in P\) and \(\ell\) large enough,
\[
\frac{f^{\ell}_{\lambda^{(\ell)}}, \gamma}{f^{\ell}_{\lambda^{(\ell)}}} = \frac{f^{\ell}_{\lambda^{(\ell)}}, -\gamma}{f^{\ell}_{\lambda^{(\ell)}}} = \frac{\mathbb{P}(W_\ell = \lambda^{(\ell)} - \gamma, W_\ell \in C \text{ for any } t \in [0, \ell])}{\mathbb{P}(W_\ell = \lambda^{(\ell)}, W_\ell \in C \text{ for any } t \in [0, \ell])},
\]
this last quotient tending to 1 when \(\ell\) tends to infinity by Proposition 7.1. This implies
\[
\lim_{\ell \to +\infty} \frac{f^\ell_{\lambda^{(\ell)}}, \mu}{f^\ell_{\lambda^{(\ell)}}} = \tau^{-\mu} \sum_{\gamma \in P} K_{\mu, \gamma} \tau^{-\gamma} = \tau^{-\mu} S_\mu(\tau).
\]

We have thus proved the following consequence of Theorem 6.2.

**Corollary 7.2.** For any \(\mu \in Q \cap P_+\) and any sequence of dominant weights of the form \(\lambda^{(\ell)} = \ell m(1) + o(\ell)\), we have \(\lim_{\ell \to +\infty} \frac{f^\ell_{\lambda^{(\ell)}}, \mu}{f^\ell_{\lambda^{(\ell)}}} = \tau^{-\mu} S_\mu(\tau)\).

**Remark.** One can regard this corollary as an analogue of the asymptotic behavior of the number of paths in the Young lattice obtained by Kerov and Vershik (see [8] and the references therein).

7.2. **Probability that \(W\) stays in \(C\).** By Theorem 6.2 we can compute \(\mathbb{P}_\mu(W(t) \in C \text{ for any } t \in [0, \ell])\). Unfortunately, this does not permit us to make explicit \(\mathbb{P}_\mu(W_\ell \in C \forall \ell \geq 1)\). Nevertheless, we have the immediate inequality
\[
\mathbb{P}_\mu(W(t) \in C \text{ for any } t \geq 0) \leq \mathbb{P}_\mu(W_\ell \in C \text{ for any } \ell \geq 1).
\]
Since we have assumed that \(g\) is of finite type, each crystal \(B(\pi_x)\) is finite. For any \(i = 1, \ldots, n\), write \(m_0(i) \geq 1\) for the maximal length of the \(i\)-chains appearing
in $B(\pi_\kappa)$. Set $\kappa_0 = \sum_{i=1}^n (m_0(i) - 1) \omega_i$. Observe that $\kappa_0 = 0$ if and only if $\kappa$ is a minuscule weight.

**Lemma 7.3.** Assume $W_k \in C$ for any $k = 1, \ldots, \ell$. Then $\kappa_0 + \mathcal{W}(t) \in C$ for any $t \in [0, \ell]$.

**Proof.** Since $\kappa_0$ is a dominant weight, we can consider $\pi_{\kappa_0}$ any path from 0 to $\kappa_0$ which remains in $C$. First observe that the hypothesis $W_k \in C$ for any $k = 1, \ldots, \ell$ is equivalent to $\kappa_0 + \mathcal{W}(k) \in \kappa_0 + C$ for any $k = 1, \ldots, \ell$. We also know by assertion (8) of Theorem 3.6 that $B(\pi_{\kappa_0}) \otimes B(\pi_\kappa)^{\otimes \ell}$ is contained in $\mathcal{L}_{\min, \kappa}$ for any $\ell \geq 1$. Set $\mathcal{W}(\ell) = \pi_1 \otimes \cdots \otimes \pi_\ell$. By assertion (3) of Proposition 3.5, we have to prove that $\tilde{e}_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_\ell) = 0$ for any $i = 1, \ldots, n$ providing $\text{wt}(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_k) = \pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_k(1) \in \kappa_0 + P_+$ for any $k = 1, \ldots, \ell$. Fix $i = 1, \ldots, n$. Set $\kappa_0(i) = m_0(i) - 1$. We proceed by induction.

Assume $\ell = 1$. Since we have $\tilde{e}_i(\pi_{\kappa_0}) = 0$, it suffices to prove by using assertion (2) of Proposition 3.5 that $e_i(\pi_{\kappa_0}) = \varphi_i(\pi_{\kappa_0})$. By definition of the dominant weight $\pi_{\kappa_0}$, we have $\varphi_i(\pi_{\kappa_0}) = \kappa_0(i)$. So we have to prove that $e_i(\pi_1) \leq \kappa_0(i)$. Assertion (7) of Theorem 3.6 and the hypothesis $\text{wt}(\pi_{\kappa_0} \otimes \pi_1) \in \kappa_0 + P_+$ permit us to write

$$\text{wt}(\pi_{\kappa_0})_i + \text{wt}(\pi_1)_i = \text{wt}(\pi_{\kappa_0} \otimes \pi_1)_i \geq \kappa_0(i).$$

Recall that $\pi_1$ belongs to $B(\pi_\kappa)$. So $e_i(\pi_1) \leq \kappa_0(i) + 1$ because $e_i(\pi_1)$ gives the distance of $\pi_1$ from the source vertex of its $i$-chain. When $e_i(\pi_1) < \kappa_0(i) + 1$ we are done. So assume $e_i(\pi_1) = \kappa_0(i) + 1$. This means that $\pi_1$ satisfies $\varphi_i(\pi_1) = 0$. Therefore, $\text{wt}(\pi_1)_i = -\kappa_0(i) - 1$. But in this case, we get by \(35\)

$$\text{wt}(\pi_{\kappa_0} \otimes \pi_1)_i = \kappa_0(i) - (\kappa_0(i) + 1) = -1 \geq \kappa_0(i),$$

hence a contradiction.

Now assume $\tilde{e}_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1}) = 0$ for any $k = 1, \ldots, \ell - 1$. Observe that

$$\text{wt}(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1})_i = \varphi_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1}) \geq \kappa_0(i)$$

since $\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1} \in \kappa_0 + P_+$ and $\tilde{e}_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1}) = 0$. We also have

$$\text{wt}(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1} \otimes \pi_\ell)_i = \text{wt}(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1})_i + \text{wt}(\pi_\ell)_i \geq \kappa_0(i).$$

We proceed as in the case $\ell = 1$. Assume first $e_i(\pi_\ell) \leq \varphi_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1})$. Then by Proposition 3.5 and the induction equality $\tilde{e}_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1}) = 0$, we have $\tilde{e}_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1}) = 0$.

Now assume

$$e_i(\pi_\ell) > \varphi_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1}).$$

Since $\varphi_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1}) \geq \kappa_0(i)$ and $\pi_\ell \in B(\pi_{\kappa_0})$, we must have $e_i(\pi_\ell) = \kappa_0(i) + 1$, $\varphi_i(\pi_\ell) = 0$ and $\varphi_i(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1}) = \kappa_0(i)$. Therefore, we get

$$\text{wt}(\pi_\ell)_i = -\kappa_0(i) - 1$$

and

$$\text{wt}(\pi_{\kappa_0} \otimes \pi_1 \otimes \cdots \otimes \pi_{\ell-1}) = \kappa_0(i).$$

Then \(35\) yields the contradiction

$$-1 \geq \kappa_0(i).$$

\[ \square \]

**Remark.** In general the assertion $W_k \in C$ for any $k = 1, \ldots, \ell$ is not equivalent to the assertion $\kappa_0 + \mathcal{W}(t) \in \kappa_0 + C$ for any $t \in [0, \ell]$. This is nevertheless true when $\kappa$ is a minuscule weight since $\kappa_0 = 0$ in this case and the paths in $B(\pi_\kappa)$ are lines.

We deduce from the previous lemma the inequality

$$\mathbb{P}_\mu(W_k \in C \text{ for any } k = 0, \ldots, \ell) \leq \mathbb{P}_{\mu + \kappa_0}(\mathcal{W}(t) \in C \text{ for any } t \in [0, \ell]).$$
When $\ell$ tends to infinity, this yields

$$P_\mu(W_\ell \in C \text{ for any } \ell \geq 1) \leq P_\mu(W(t) \in C \text{ for any } t \geq 0).$$

By using Theorem 6.2, this implies

**Theorem 7.4.** Assume $\mathfrak{g}$ is of finite type (then $m_\alpha = 1$ for any $\alpha \in R_+$. Then, for any $\mu \in P_+$ we have

$$\prod_{\alpha \in R_+} (1 - \tau^\alpha)S_\mu(\tau) \leq P_\mu(W_\ell \in C \text{ for any } \ell \geq 1) \leq \prod_{\alpha \in R_+} (1 - \tau^\alpha)S_{\mu+\kappa_0}(\tau).$$

In particular, we recover the result of Corollary 7.4.3 in [10]:

$$P_\mu(W_\ell \in C \text{ for any } \ell \geq 1) = \prod_{\alpha \in R_+} (1 - \tau^\alpha)S_\mu(\tau)$$

when $\kappa$ is minuscule.

**Remark.** The inequality obtained in the previous theorem can also be rewritten as

$$1 \leq \frac{P_\mu(W_\ell \in C \text{ for any } \ell \geq 1)}{P_\mu(W(t) \in C \text{ for any } t \in [0, +\infty[)} \leq \frac{S_{\mu+\kappa_0}(\tau)}{S_\mu(\tau)}.$$

When $\mu$ tends to infinity, we thus have $P_\mu(W_\ell \in C \forall \ell \geq 1) \sim P_\mu(W(t) \in C \text{ for any } t \geq 0)$ as expected.

8. Appendix (Proof of Proposition 2.1)

By definition of the probability $Q$, for any $\ell \geq 1$ and any $\mu_0, \ldots, \mu_\ell, \lambda \in C$, one gets

$$Q(Y_{\ell+1} = \lambda \mid Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0) = \frac{Q(Y_{\ell+1} = \lambda, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)}{Q(Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)} = \frac{P(E, Y_{\ell+1} = \lambda, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)}{P(E, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)} =: \frac{N_\ell}{D_\ell}.$$

We first have, using the Markov property,

$$N_\ell = P(Y(t) \in C \text{ for } t \geq 1, Y_{\ell+1} = \lambda, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)$$

$$= P(Y(t) \in C \text{ for } t \geq \ell + 1 \mid Y_{\ell+1} = \lambda, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)$$

$$\times P(Y_{\ell+1} = \lambda, Y(t) \in C \text{ for } t \in [0, \ell + 1], Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)$$

$$= P(Y(t) \in C \text{ for } t \geq \ell + 1 \mid Y_{\ell+1} = \lambda)$$

$$\times P(Y_{\ell+1} = \lambda, Y(t) \in C \text{ for } t \in [0, \ell + 1[, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)$$

$$= P(Y(t) \in C \text{ for } t \geq 0 \mid Y_0 = \lambda)$$

$$\times P(Y_{\ell+1} = \lambda, Y(t) \in C \text{ for } t \in [0, \ell + 1[, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)$$

with

$$P(Y_{\ell+1} = \lambda, Y(t) \in C \text{ for } t \in [0, \ell + 1[, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)$$

$$= P(Y_{\ell+1} = \lambda, Y(t) \in C \text{ for } t \in [\ell, \ell + 1[ ] Y(t) \in C \text{ for } t \in [0, \ell[, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)$$

$$\times P(Y(t)) \in C \text{ for } t \in [0, \ell[, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0)$$

$$= P(Y_{\ell+1} = \lambda, Y(t) \in C \text{ for } t \in [\ell, \ell + 1[ ) Y_\ell = \mu_\ell) \times P(Y(t) \in C \text{ for } t \in [0, \ell[, Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0).$$
We therefore obtain
\[ N_\ell = \mathbb{P}(E \mid Y_0 = \lambda) \times \mathbb{P}(Y_{\ell+1} = \lambda, \mathcal{Y}(t) \in \mathcal{C} \text{ for } t \in [\ell, \ell+1] \mid Y_\ell = \mu_\ell) \times \mathbb{P}(\mathcal{Y}(t) \in \mathcal{C} \text{ for } t \in [0, \ell], Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0). \]

A similar computation yields
\[ D_\ell = \mathbb{P}(E \mid Y_\ell = \mu_\ell) \times \mathbb{P}(Y_{\ell+1} = \lambda, \mathcal{Y}(t) \in \mathcal{C} \text{ for } t \in [0, \ell], Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0). \]

Finally, we get
\[ Q(Y_{\ell+1} = \lambda \mid Y_\ell = \mu_\ell, \ldots, Y_0 = \mu_0) = \frac{\mathbb{P}(Y_{\ell+1} = \lambda, \mathcal{Y}(t) \in \mathcal{C} \text{ for } t \in [\ell, \ell+1] \mid Y_\ell = \mu_\ell) \times \mathbb{P}(E \mid Y_0 = \lambda)}{\mathbb{P}(E \mid Y_0 = \mu_\ell)}. \]

REFERENCES

[1] Philippe Biane, Philippe Bougerol, and Neil O’Connell, Littelmann paths and Brownian paths, Duke Math. J. 130 (2005), no. 1, 127–167, DOI 10.1215/S0012-7094-05-13014-9. MR2176549
[2] N. Bourbaki, Éléments de mathématique. Fasc. XXXIV. Groupes et algèbres de Lie. Chapitre IV: Groupes de Coxeter et systèmes de Tits. Chapitre V: Groupes engendrés par des réflexions. Chapitre VI: systèmes de racines (French), Actualités Scientifiques et Industrielles, No. 1337, Hermann, Paris, 1968. MR0240238 (39 #1590)
[3] Brian C. Hall, Lie groups, Lie algebras, and representations, An elementary introduction, Graduate Texts in Mathematics, vol. 222, Springer-Verlag, New York, 2003. MR1997306
[4] Jin Hong and Seok-Jin Kang, Introduction to quantum groups and crystal bases, Graduate Studies in Mathematics, vol. 42, American Mathematical Society, Providence, RI, 2002. MR1881971 (2002m:17012)
[5] A. Joseph, Lie algebras, their representation and crystals, lecture notes, Weizman Institute.
[6] Victor G. Kac, Infinite-dimensional Lie algebras, 3rd ed., Cambridge University Press, Cambridge, 1990. MR1104219 (92k:17038)
[7] Masaki Kashiwara, On crystal bases, Representations of groups (Banff, AB, 1994), CMS Conf. Proc., vol. 16, Amer. Math. Soc., Providence, RI, 1995, pp. 155–197. MR1357199 (97a:17016)
[8] S. V. Kerov, Asymptotic representation theory of the symmetric group and its applications in analysis, translated from the Russian manuscript by N. V. Tsilevich, with a foreword by A. Vershik and comments by G. Olshanski, Translations of Mathematical Monographs, vol. 219, American Mathematical Society, Providence, RI, 2003. MR1984868 (2005b:20021)
[9] Cédric Lecouvey, Combinatorics of crystal graphs for the root systems of types $A_n,B_n,C_n,D_n$ and $G_2$, Combinatorial aspect of integrable systems, MSJ Mem., vol. 17, Math. Soc. Japan, Tokyo, 2007, pp. 11–41. MR2269126 (2008b:05183)
[10] Cédric Lecouvey, Emmanuel Lesigne, and Marc Peigné, Random walks in Weyl chambers and crystals, Proc. Lond. Math. Soc. (3) 104 (2012), no. 2, 323–358, DOI 10.1112/plms/pdr033. MR2880243
[11] C. Lecouvey, E. Lesigne, and M. Peigné, Conditioned one-way simple random walks and representation theory, preprint, arXiv 1202.3604 (2012), to appear in Séminaire Lotharingien de Combinatoire.
[12] Peter Littelmann, A Littlewood-Richardson rule for symmetrizable Kac-Moody algebras, Invent. Math. 116 (1994), no. 1-3, 329–346, DOI 10.1007/BF01231564. MR1253196 (95f:17023)
[13] Peter Littelmann, Paths and root operators in representation theory, Ann. of Math. (2) 142 (1995), no. 3, 499–525, DOI 10.2307/2118553. MR1356780 (96m:17011)
[14] Peter Littelmann, The path model, the quantum Frobenius map and standard monomial theory, Algebraic groups and their representations (Cambridge, 1997), NATO Adv. Sci. Inst. Ser. C Math. Phys. Sci., vol. 517, Kluwer Acad. Publ., Dordrecht, 1998, pp. 175–212. MR1670770 (99m:20096)
[15] Neil O’Connell, *A path-transformation for random walks and the Robinson-Schensted correspondence*, Trans. Amer. Math. Soc. 355 (2003), no. 9, 3669–3697 (electronic), DOI 10.1090/S0002-9947-03-03226-4. MR1990168 (2004f:60109)

[16] Neil O’Connell, *Conditioned random walks and the RSK correspondence*, J. Phys. A 36 (2003), no. 12, 3049–3066, DOI 10.1088/0305-4470/36/12/312. Random matrix theory. MR1986407 (2004e:05201)

[17] Wolfgang Woess, *Denumerable Markov chains*, Generating functions, boundary theory, random walks on trees, EMS Textbooks in Mathematics, European Mathematical Society (EMS), Zürich, 2009. MR2548569 (2011f:60142)

Laboratoire de Mathématiques et Physique Théorique (UMR CNRS 7350), Université François-Rabelais, Tours, Fédération de Recherche Denis Poisson - CNRS, Parc de Grandmont, 37200 Tours, France

E-mail address: cedric.lecouvey@lmpt.univ-tours.fr

Laboratoire de Mathématiques et Physique Théorique (UMR CNRS 7350), Université François-Rabelais, Tours, Fédération de Recherche Denis Poisson - CNRS, Parc de Grandmont, 37200 Tours, France

E-mail address: emmanuel.lesigne@lmpt.univ-tours.fr

Laboratoire de Mathématiques et Physique Théorique (UMR CNRS 7350), Université François-Rabelais, Tours, Fédération de Recherche Denis Poisson - CNRS, Parc de Grandmont, 37200 Tours, France

E-mail address: marc.peigne@lmpt.univ-tours.fr