Combinatorial analysis of magnetic configurations

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Abstract

Properties of polynomial coefficients are applied to investigation of finite spin systems. Number of spin-configurations states with a given total magnetization are calculated by recurrence formulas for polynomial coefficients and for sum of polynomial coefficients.

1 Introduction

There is a big interest in application of the so-called 'finite lattice method' due to easy computer calculations or simulations. A dimension of state space is finite and, theoretically, one can obtain exact results. It is very important to analyze a state space before starting computer program in order to simplify calculations by, for example, decomposition of the space into subspaces with given properties. A spin system with its total magnetization as 'a given property' is a very nice example of such procedure.

The finite spin system can be described as follows [1] (cf. also [2, 3] in this volume and references quoted therein):

1. There is a given set of nodes of crystal lattice
$$X := \underline{n} := \{1, 2, \ldots, n\}. \tag{1}$$
2. Each node carries spin s determined by a spin number $s \geq 0$ (integer or half-integer).
3. Possible spin projections on a quantization axis form an $(2s+1)$-element set
$$Y := [-s, +s] := \{-s, -s+1, \ldots, +s\}. \tag{2}$$
4. The *spin-configurations* of the considered spin system are the mappings $f : X \to Y$, hence the set of spin-configurations is determined as
$$Y^X := \mathrm{Map}(\underline{n}, [-s, +s]) := \{f : X \to Y\} \tag{3}$$
and consists of $|Y^X| = (2s+1)^n$ elements.

One can used Dirac's notation and writes a spin-configuration as the so-called ket

$$|i_1, i_2, \ldots, i_n\rangle, \quad i_j \in Y, \ \ j \in X, \tag{4}$$

where $i_j = f(j)$. The set Y^X is an orthonormal basis of a space L of all quantum states of magnet over the field of complex numbers $\mathbb{C}$ [2, 3]. For $s = 1/2$ we will use a set $Y = \{-, +\}$ instead of $\{-1/2, +1/2\}$ for the sake of simplicity. In this case the set of all configurations coincides with the power set 2^X of X.

The most important operator acting in the space L is the energy operator, i.e. the Hamiltonian. It is well known, that two commuting operators have the same set of eigenfunctions, so the states can be labelled simultaneously by two (or more) eigenvalues. These eigenvalues are called 'good quantum numbers'. For almost all magnetic systems (Hamiltonians) a total magnetization is a good quantum number. It is the eigenvalue of an operator

$$S^z := \sum_{j \in X} s_j^z, \tag{5}$$

where s_j^z is a one-site operator and $s_j^z |i_j\rangle = i_j |i_j\rangle$ so

$$S^z |i_1, i_2, \ldots, i_n\rangle = \left(\sum_{j \in X} i_j \right) |i_1, i_2, \ldots, i_n\rangle = M |i_1, i_2, \ldots, i_n\rangle. \tag{6}$$

It is obvious that all possible values of the total magnetization form a set

$$Z := [-ns, +ns] = \{-ns, -ns + 1, \ldots, +ns\}, \ \ |Z| = 2ns + 1. \tag{7}$$

In this paper we present a method for calculating number of configurations with a given magnetization M. The Hamiltonian of the considered system is irrelevant and it will be omitted in discussion. It is easy to notice that the operator S^z commutes with any permutation $\sigma \in S_{\underline{n}}$, so this group is a symmetry group of our problem.

2 Polynomial coefficients

Let $\Omega(m, n) \subset \mathbb{Z}^{\underline{m}}$ be a set of all m-tuples $(k_1, k_2, \ldots, k_m)$ such that

$$\mathbb{Z}^{\underline{m}} \supset \Omega(m, n) := \{\underline{K} = (k_1, k_2, \ldots, k_m) \mid k_i \geq 0, \sum_{i \in \underline{m}} k_i = n\}. \tag{8}$$

The n-th power of polynomial $\mathcal{P}_{(m)} = \sum_{i \in \underline{m}} x_i$, $x_i \in \mathbb{C}$, can be written as

$$\mathcal{P}_{(m)}^n = \sum_{\underline{K} \in \Omega(m,n)} [n \mid \underline{K}] \prod_{i \in \underline{m}} x_i^{k_i}, \tag{9}$$

where $[n \mid \underline{K}]$ is a polynomial coefficient

$$[n \mid \underline{K}] := \frac{n!}{\prod_{i \in \underline{m}} k_i!}. \tag{10}$$

For $m = 2$ one obtains the Newton binomial coefficient

$$[n \mid (k, n-k)] = \left(\begin{array}{c} n \\ k \end{array} \right) = \frac{n!}{k!(n-k)!} \tag{11}$$

and the well-known formula

$$(x_1 + x_2)^n = \sum_{k \in [0,n]} \left(\begin{array}{c} n \\ k \end{array} \right) x_1^k x_2^{(n-k)}. \tag{12}$$

The properties of these coefficients are gathered in Table 1 and compared with the properties of the binomial coefficients. A mnemonic scheme corresponds to the first recurrence procedure. In the case $m = 2$ the well-known Pascal triangle (drawn in a two-dimensional space) is obtained, whereas in the general case a similar scheme should be drawn in a m-dimensional space and we can call it a *(m-dimensional) Pascal 'simplex'*. Figure 1 presents an example for $m = 3$ ('Pascal tetrahedron'). This general scheme has the same properties as the ordinary Pascal triangle (cf. Table 1):

1. Subsequent 'bases' of simplex, labelled by n, consists of $\frac{(n+m-1)!}{n!(m-1)!}$ entries.
2. The sum of entries in the n-th row is equal to m^n.
3. The first recurrence formula (with respect to n) is satisfied.

Table 1: Properties of polynomial coefficients

	general case	$m = 2$
Number of different coefficients	$\binom{n+m-1}{m-1}$	$n+1$
Sum rules	$\sum_{\underline{K} \in \Omega(m,n)} [n \mid \underline{K}] = m^n$ $\sum_{\underline{K} \in \Omega(m,n)} \exp\left[\frac{2\pi i}{m} \sum_{i \in \underline{m}} i k_i\right] [n \mid \underline{K}] = 0$	$\sum_{k \in [0,n]} \binom{n}{k} = 2^n$ $\sum_{k \in [0,n]} (-1)^k \binom{n}{k} = 0$
Recurrences: 1. with respect to power n	$[n \mid \underline{K}] = \sum_{i \in \underline{m}} [n-1 \mid \underline{K}^{(j)}]$, $\underline{K}^{(j)} = (k_1, \ldots, k_j - 1, \ldots, k_m)$ $\underline{K}^{(j)} \subset \Omega(m, n-1)$	$\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$
2. with respect to number of variables m[1]	$[n \mid \underline{K}] = [n \mid (k_1, n-k_1)] \times [n-k_1 \mid \underline{K}_1']$, $\underline{K}_1' = (k_2, k_3, \ldots, k_m)$ $\underline{K}_1' \subset \Omega(m-1, n-k_1)$	$\binom{n}{k} = \binom{n}{k} \frac{(n-k)!}{(n-k)!}$

It is easy to notice that each m'-dimensional, $m' \leq m$, 'wall' of the simplex is also a Pascal simplex corresponding to m'-nomial coefficients (see Figure 1). It is in the accordance with the second recurrence formula[1].

[1] This formula is trivial for $m = 2$ and for $m \geq 3$ any element k_i, $i \in \underline{m}$, can be considered.

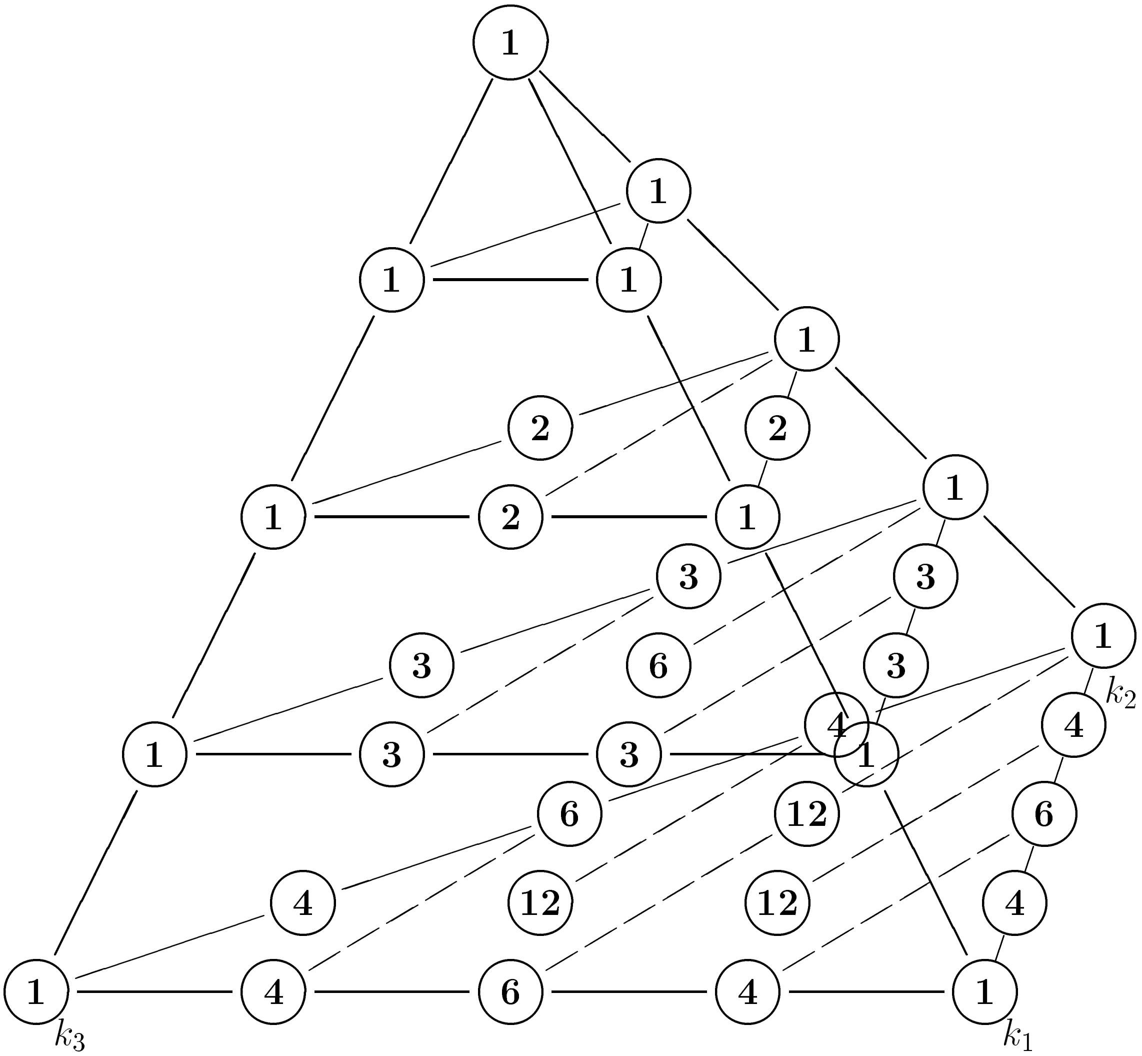

Figure 1: An example of the Pascal simplex, $m = 3$, $n \leq 4$. Dashed lines connect points with the same $\sum_{i \in \underline{m}} ik_i$ (cf. Sec. 4 Eq. (29))

Let $\mathbf{A}$ be a linear function $\mathbf{A} : \Omega(m, n) \to \mathbb{R}$ given as

$$\mathbf{A}(\underline{K}) = \sum_{i \in \underline{m}} \alpha_i k_i \tag{13}$$

and determined by real coefficients $\alpha_i \in \mathbb{R}$ (so this function can be identified with an m-tuple $(\alpha_1, \alpha_1, \ldots, \alpha_m)$). For each $a \in \mathbf{A}(\Omega(m, n))$ one can find its counter-image

$$\mathbf{A}^{-1}(a) = \{\underline{K} \in \Omega(m, n) \mid \mathbf{A}(\underline{K}) = a\}. \tag{14}$$

For given m, n, and $\mathbf{A}$ we introduce the function $\mathcal{A}^{n,m} : \mathbb{R} \to \mathbb{Z}_+$

$$\mathcal{A}^{n,m}(a) := \sum_{\underline{K} \in A^{-1}(a)} [n \mid \underline{K}]. \tag{15}$$

The recurrence formulas for polynomial coefficients yield similar ones for the function $\mathcal{A}^{n,m}$. That is,

$$\mathcal{A}^{n,m}(a) = \sum_{i\in\underline{m}} \mathcal{A}^{n-1,m}(a-\alpha_i) \tag{16}$$

with the initial condition

$$\mathcal{A}^{1,m}(a) = \sum_{i\in\underline{m}} \delta(\alpha_i, a), \tag{17}$$

and the second one in the form

$$\mathcal{A}^{n,m}(a) = \sum_{k\in\Delta} \left(\begin{array}{c} n \\ k \end{array}\right) \mathcal{A}^{n-k,m-1}(a-\alpha_1 k), \tag{18}$$

where

$$\Delta := \{k \in [0,n] \mid (n-k)\alpha \leq (a-\alpha_1 k) \leq (n-k)\beta\} \tag{19}$$

with α and β being $\min(\alpha_2, \alpha_3, \ldots, \alpha_m)$ and $\max(\alpha_2, \alpha_3, \ldots, \alpha_m)$, respectively. Of course, the other coefficient α_i can be taken into account (cf. Table 1). The initial formula for $m = 2$ has the following form

$$\mathcal{A}^{n,2}(a) = \sum_{(k,n-k)\in\mathbf{A}^{-1}(a)} \left(\begin{array}{c} n \\ k \end{array}\right) = \begin{cases} 2^n & \text{if } \alpha_1 = \alpha_2, \\ \binom{n}{k} & \text{for } \alpha_1 \neq \alpha_2,\ k = \frac{a-\alpha_2 n}{\alpha_1-\alpha_2}. \end{cases} \tag{20}$$

Let's consider, e.g., a function (13) determined by the m-tuple $\mathbf{N} := (1,1,\ldots,1)$, i.e. $\alpha_i = 1$, $i \in \underline{m}$. Then

$$\mathbf{N}(\underline{K}) = \sum_{i\in\underline{m}} 1 \cdot k_i = n, \quad \text{for each } \underline{K} \in \Omega(m,n), \tag{21}$$

so $\mathbf{N}(\Omega(m,n)) = \{n\}$. Therefore, for the function (15) one obtains

$$\mathcal{N}^{n,m}(n) = \sum_{\underline{K}\in\Omega(m,n)} [n \mid \underline{K}] = m^n. \tag{22}$$

The first recurrence formula (16) yields

$$\mathcal{N}^{n,m}(n) = \sum_{i\in\underline{m}} \mathcal{N}^{n-1,m}(n-1) = \sum_{i\in\underline{m}} m^{n-1} = m \cdot m^{n-1}, \tag{23}$$

so it is, of course, the well-known recurrence formula for the power m^n. From the second recurrence formula (18) one obtains (the set Δ contains all integers $0, 1, \ldots, n$, see Eq. (19))

$$\begin{aligned} \mathcal{N}^{n,m}(n) &= \sum_{k\in[0,n]} \left(\begin{array}{c} n \\ k \end{array}\right) \mathcal{N}^{n-k,m-1}(n-k) = \sum_{k\in[0,n]} \left(\begin{array}{c} n \\ k \end{array}\right) (m-1)^{n-k} \\ &= \sum_{k\in[0,n]} \left(\begin{array}{c} n \\ k \end{array}\right) (m-1)^{n-k} \cdot 1^k = (1 + (m-1))^n. \end{aligned} \tag{24}$$

So, in this case, the recurrence formula is less useful, but evidently true.

3 Orbits of symmetric group

The symmetric group $S_{\underline{n}}$ acts on the set Y^X of all spin-configurations in the following way [2, 3]

$$P : S_{\underline{n}} \times Y^X \to Y^X, \quad P(\sigma) = \begin{pmatrix} f \\ f \circ \sigma^{-1} \end{pmatrix}, \quad f \in Y^X, \quad \sigma \in S_{\underline{n}}. \tag{25}$$

This action determines orbits

$$O(f) = \{ f \circ \sigma^{-1} \mid \sigma \in S_{\underline{n}} \}. \tag{26}$$

For each $\underline{K} \in \Omega(m, n)$ there exists an orbit with the representative

$$f^0 := \left| i_1^0, i_2^0, \ldots, i_n^0 \right\rangle := |\underbrace{-s, \ldots, -s}_{k_1 \text{ times}}, \underbrace{-s+1, \ldots, -s+1}_{k_2 \text{ times}}, \ldots, \underbrace{+s, \ldots, +s}_{k_m \text{ times}} \rangle, \tag{27}$$

where $m = |Y| = 2s + 1$. It is evident that orbits can be labelled by the m-tuples $\underline{K} \in \Omega(m, n)$, so they will be denoted hereafter as $O_{\underline{K}}$. These orbits have the following properties:

1. Cardinality of an orbit: $|O_{\underline{K}}| = [n \mid \underline{K}]$.

2. Stabilizer: $G_{\underline{K}} \cong S_{\underline{n}} / \bigotimes_{i \in \underline{m}} S_{\underline{k_i}}$ (quotient group of the symmetric group $S_{\underline{n}}$ and the Young subgroup $\bigotimes_{i \in \underline{m}} S_{\underline{k_i}}$).

3. Number of different orbits: $[n + 2s \mid (n, 2s)]$ ($n + 1$ for $s = 1/2$, i.e. for $m = 2$).

4. Number of all configurations:

$$\sum_{\underline{K} \in \Omega(m,n)} [n \mid \underline{K}] = (2s+1)^n = \sum_{\underline{K} \in \Omega(m,n)} |O_{\underline{K}}|. \tag{28}$$

4 Classification of configurations

Let's consider a function (13) determined by the m-tuple $\mathbf{M} := (-s, -s+1, \ldots, +s)$, i.e. $\alpha_i = i - s - 1$, $i \in \underline{m}$. Then

$$\begin{aligned} \mathbf{M}(\underline{K}) &= \sum_{i \in \underline{m}} (i - s - 1) k_i = -n(s+1) + \sum_{i \in \underline{m}} i k_i = \sum_{\mu \in Y} \mu k_{\mu + s + 1} \\ &= k_1(-s) + k_2(-s+1) + \ldots + k_{2s+1} s = M_{\underline{K}}, \end{aligned} \tag{29}$$

where $M_{\underline{K}}$ is a magnetization of any configuration in the orbit $O_{\underline{K}}$ (see Eqs. (6) and (27)). Therefore, the image of the set $\Omega(m, n)$ is $\mathbf{M}(\Omega(m, n)) = Z$ given by Eq. (7) and each value of the function (cf. Sec. 3)

$$\mathcal{M}^{n,2s+1}(M) = \sum_{\underline{K} \in \mathbf{M}^{-1}(M)} [n \mid \underline{K}] = \sum_{\underline{K} \in \mathbf{M}^{-1}(M)} |O_{\underline{K}}| \tag{30}$$

determines a number of spin-configurations with a given total magnetization $M \in Z$ (for a given number n of spins s). It is important to underline that for all n and s

$$\mathcal{M}^{n,2s+1}(M) = \mathcal{M}^{n,2s+1}(-M), \quad M \in Z. \tag{31}$$

The recurrence formulas described by Eqs. (16,18) yield the procedures for the calculation of $\mathcal{M}^{n,2s+1}(M)$. From the first formula one can easy find

$$\mathcal{M}^{n,2s+1}(M) = \sum_{i\in\underline{m}} \mathcal{M}^{n-1,2s+1}(M - i + s + 1) = \sum_{\mu\in Y} \mathcal{M}^{n-1,2s+1}(M - \mu) \tag{32}$$

with the starting condition

$$\mathcal{M}^{1,2s+1}(M) = \begin{cases} 1 & \text{for } M \in [-s,+s] = Y, \\ 0 & \text{in other cases.} \end{cases} \tag{33}$$

One can introduce in a formal way the function $\mathcal{M}^{0,2s+1}$ as

$$\mathcal{M}^{0,2s+1}(M) := \delta_{M,0}. \tag{34}$$

It is easy to notice that with this definition (34) a mnemonic scheme, like the Pascal triangle, can be constructed for this recurrence procedure. Examples of such scheme are presented in Figure 2 and 3 for $s = 1/2, 1$ and $s = 3/2$, respectively. This 'extended' Pascal triangle has the following properties (of course, for $s = 1/2$, $m = 2$ they coincide with the properties of the Pascal triangle):

1. There are $|Z| = |[-ns, +ns]| = 2ns + 1$ nonzero entries in the n-th row.
2. Each number in the n-th row is a sum of $|Y| = |[-s, +s]| = 2s + 1$ numbers from the $(n-1)$-th row. These numbers are the 'nearest-neighbor' of calculated entry (see Figures 2 and 3).

From the second recurrence formula the following rule is obtained

$$\mathcal{M}^{n,2s+1}(M) = \sum_{k\in\Delta} \binom{n}{k} \mathcal{M}^{n-k,2s}(M + sk), \tag{35}$$

where

$$\Delta = \{k \in [0,n] \mid n(1-s) - M \le k \le (ns - M)/2s\} \tag{36}$$

with the initial condition

$$\mathcal{M}^{n,2}(M) = \binom{n}{n/2 - M} = [n \mid (\frac{n}{2} - M, \frac{n}{2} + M)]. \tag{37}$$

This procedure can be called *the recurrence with respect to spin* (since one can introduce a new spin $s' = s - 1/2$, so $2s' + 1 = 2s = m - 1$), whereas the previous is *the recurrence with respect to number of spins.*

5 Examples

A. $n = 2$
One can easy find that

$$\mathcal{M}^{2,2s+1} = \sum_{\mu\in Y} \mathcal{M}^{1,2s+1}(M - m) = \sum_{\mu\in Y} \sum_{\mu'\in Y} \delta(\mu', M - \mu) = 2s + 1 - |M|.$$

Table 2: Results for $n = 3$ and $s = 3/2$ ($m = 4$) for non-negative M

Orbit number	$\underline{K}$	Representative	$M_{\underline{K}}$	$\lvert O_{\underline{K}}\rvert$	$\mathcal{A}^{3,4}(M)$
1	(1,0,1,1)	$\lvert -3/2, +1/2, +3/2\rangle$	1/2	6	
2	(0,2,0,1)	$\lvert -1/2, -1/2, +3/2\rangle$	1/2	3	
3	(0,1,2,0)	$\lvert -1/2, +1/2, +1/2\rangle$	1/2	3	12
4	(1,0,0,2)	$\lvert -3/2, +3/2, +3/2\rangle$	3/2	3	
5	(0,1,1,1)	$\lvert -1/2, +1/2, +3/2\rangle$	3/2	6	
6	(0,0,3,0)	$\lvert +1/2, +1/2, +1/2\rangle$	3/2	1	10
7	(0,1,0,2)	$\lvert -1/2, +3/2, +3/2\rangle$	5/2	3	
8	(0,0,2,1)	$\lvert +1/2, +1/2, +3/2\rangle$	5/2	3	6
9	(0,0,1,2)	$\lvert +1/2, +3/2, +3/2\rangle$	7/2	3	3
10	(0,0,0,3)	$\lvert +3/2, +3/2, +3/2\rangle$	9/2	1	1

B. $s = 1/2$

For each $M \in [-n/2, +n/2]$ there exists only one orbit with the representative

$$|\underbrace{-,-,\ldots,-}_{n/2-M \text{ times}},\underbrace{+,+,\ldots,+}_{n/2+M \text{ times}}\rangle,$$

so number of configurations with a given magnetization equals the cardinality of the orbit

$$O_{(n/2-M,n/2+M)} = \binom{n}{n/2-M}.$$

C. $M = ns$

There exists only one solution $\underline{K}^0 = (0, 0, \ldots, 0, n)$ of the equation $\mathbf{M}(\underline{K}) = ns$. Therefore

$$\mathcal{M}^{n,2s+1}(ns) = [n \mid \underline{K}^0] = 1.$$

a) $s = 1/2$

n \ M	...	-2	$-\frac{3}{2}$	-1	$-\frac{1}{2}$	0	$\frac{1}{2}$	1	$\frac{3}{2}$	2	...
0						**1**					
1					**1**		**1**				
2				**1**		**2**		**1**			
3			**1**		**3**		**3**		**1**		
4		**1**		**4**		**6**		**4**		**1**	
...	...										

b) $s = 1$

...	-4	-3	-2	-1	0	1	2	3	4	...
					1					
				1	**1**	**1**				
			1	**2**	**3**	**2**	**1**			
		1	**3**	**6**	**7**	**6**	**3**	**1**		
	1	**4**	**10**	**16**	**19**	**16**	**10**	**4**	**1**	
...										

Figure 2: 'Extended' Pascal triangles for a) $s = 1/2$ and b) $s = 1$, $n \leq 4$. Arrows correspond to the first recurrence procedure

n \ M	...	-6	$-\frac{11}{2}$	-5	$-\frac{9}{2}$	-4	$-\frac{7}{2}$	-3	$-\frac{5}{2}$	-2	$-\frac{3}{2}$	-1	$-\frac{1}{2}$	0	$\frac{1}{2}$	1	$\frac{3}{2}$	2	$\frac{5}{2}$	3	$\frac{7}{2}$	4	$\frac{9}{2}$	5	$\frac{11}{2}$	6	...
0	$s = 3/2$													**1**													
1											**1**		**1**		**1**		**1**										
2									**1**		**2**		**3**		**4**		**3**		**2**		**1**						
3						**1**		**3**		**6**		**10**		**12**		**12**		**10**		**6**		**3**		**1**			
4		**1**		**4**		**10**		**20**		**31**		**40**		**44**		**40**		**31**		**20**		**10**		**4**		**1**	
...	...																										

Figure 3: 'Extended' Pascal triangles for $s = 3/2$, $n \leq 4$. Arrows correspond to the first recurrence procedure

Table 3: Results for $n = 4$ and $s = 1$ ($m = 3$) for non-negative M

Orbit number	$\underline{K}$	Representative	$M_{\underline{K}}$	$\lvert O_{\underline{K}}\rvert$	$\mathcal{A}^{4,3}(M)$
1	(2,0,2)	$\lvert -1,-1,+1,+1\rangle$	0	6	
2	(1,2,1)	$\lvert -1,0,0,+1\rangle$	0	12	
3	(0,4,0)	$\lvert 0,0,0,0\rangle$	0	1	19
4	(1,1,2)	$\lvert -1,0,+1,+1\rangle$	1	12	
5	(0,3,1)	$\lvert 0,0,0,+1\rangle$	1	4	16
6	(1,0,3)	$\lvert -1,+1,+1,+1\rangle$	2	4	
7	(0,2,2)	$\lvert 0,0,+1,+1\rangle$	2	6	10
8	(0,1,3)	$\lvert 0,+1,+1,+1\rangle$	3	4	4
9	(0,0,4)	$\lvert +1,+1,+1,+1\rangle$	4	1	1

Hence, there is only one configuration — $|s, s, \ldots, s\rangle$ — with the maximal total magnetization $M(\underline{K}^0) = ns$.

D. $M = ns - 1$

In this case there is also one solution of the form $\underline{K}^1 = (0, 0, \ldots, 0, 1, n-1)$. Then the representative of the orbit $O_{\underline{K}^1}$ is $|s-1, s, \ldots, s\rangle$ and the cardinality of the orbit is

$$|O_{\underline{K}^1}| = [n \mid (0, 0, \ldots, 1, n-1)] = \begin{pmatrix} n \\ 1 \end{pmatrix} = n.$$

Therefore the dimension of a subspace $L_{ns-1} \subset L$, consisting of states with $S^z |\psi\rangle = (ns-1) |\psi\rangle$ is n. Moreover, this orbit does not decompose into subsets with the restriction $S_{\underline{n}}|T$, where T is the translation symmetry group of a crystal lattice. This orbit is the regular one of the group T. It is very important, since the Hamiltonian commutes with any translation, so the subspace L_{ns-1} is always an eigenspace of the Hamiltonian.

E. $n = 3,\ s = 3/2$ **and** $n = 4,\ s = 1$

The results obtained for these parameters are presented in Table 2 and 3, respectively. Please compare them with Figures 1, 2, and 3.

6 Final remarks

The properties of the polynomial coefficients and their application to the finite spin system investigation, presented in this paper, do not exhaust riches of this structure. It should be pointed at first, that the spin system is, very fine but, only one example of possible physics applications. This approach can be also useful for any problem, in which one has n elements and m equivalence classes. E.g., $[n \mid \underline{K}]$ determines a number of different states for n bosons and m admissible energy levels [4]. The second example is the Ising model and equivalent systems: lattice gas and two-component alloy [5].

On the other hand, the analysis presented in Secs. 2 and 4 does not use the generating-function method. It seems that this method would enable to perform more clear presentation and more efficient application. Moreover, the polynomial coefficients are closely connected with partitions (and then with Young diagrams) — each m-tuply $\underline{K}$ corresponds to a partition of n into no more than m non-negative integers k_i. In the similar way, the condition (29) determines a partition of $M_{\underline{K}} + n(s+1)$ into n non-negative terms no longer than $m = 2s+1$. (The sum $\sum_{i \in \underline{m}} ik_i$ determines a type of element $\pi \in S_{n(s+1)+M_{\underline{K}}}$ [6].)

The recurrence procedures for number of configuration are called the recurrence with respect to number of nodes n and to spin s, respectively. In the first one, we 'cut off' the n-th node, whereas in the next one nodes carrying the minimal spin projections ($-s$ in the first step) are removed, so the number of nodes decreases, too. A. Kerber has proposed lately a procedure in which the smallest (or the largest) projection $-s$ (or $+s$) are substituted by the next one, i.e. by $-s+1$ or $s-1$, respectively [7]. Therefore, in this method only m decreases while n is constant.

The results obtained for spin-systems and presented here are the very first step in solving an eigenproblem for a given Hamiltonian. However, this step is important, since one finds dimensions of subspaces $L_M \subset L$, $M \in Z$, which are eigenspaces of almost all magnetic Hamiltonians. For example, the ground-state of the Heisenberg antiferromagnet should have the total magnetization equal to 0. From Table 3 one obtains that for $n = 4$ and $s = 1$ the dimension of the subspace L_0 is 19, while whole space L has the dimension 81. The next step, which is necessary, is determination of bases of the subspaces L_M, i.e. one has to find a representative of each orbit $O_{\underline{K}}$. It appears that the presented recurrence procedures enable us to determine these representatives, too [8]. One of us (WF) has used them investigating the finite Heisenberg magnets and the problems can be solved very quick and in a very efficient way (see e.g. [9, 10]).

At the end, we would like to show some extensions of the polynomial coefficients. They can be written as a function $\gamma : \mathbb{Z}^r \to \mathbb{Z}$ in the form

$$\gamma(k_1, k_2, \ldots, k_r) = \frac{(\sum_{i \in \underline{r}} k_i)!}{\prod_{i \in \underline{r}} k_i!}. \tag{38}$$

This function can be extended to the space $\mathbb{R}^r$ introducing the Euler function Γ and for $\bar{x} = (x_1, x_2, \ldots, x_r) \in \mathbb{R}^r$ one obtains

$$\gamma(\bar{x}) = \frac{\Gamma(1 + \sum_{i \in \underline{r}} x_i)}{\prod_{i \in \underline{r}} \Gamma(1 + x_i)}. \tag{39}$$

This function satisfies the recurrence formulas (see Table 1)

$$\gamma(\bar{x}) = \sum_{i\in\underline{r}} \gamma(x_1,\ldots,x_i-1,\ldots,x_r), \tag{40}$$

$$\gamma(\bar{x}) = \gamma(x_1,\sum_{i=2}^{r} x_i)\gamma(x_2,x_3,\ldots,x_r). \tag{41}$$

For $r=2$ the sum-rule is also satisfied. For $x+y=n$ we have

$$\iint \gamma(x,y)\,dx\,dy = \int_{-\infty}^{\infty} \gamma(x,n-x)\,dx = 2^n, \tag{42}$$

where we applied the formula (see, e.g., [11])

$$\int_{-\infty}^{\infty} (\Gamma(c+x)\Gamma(d-x))^{-1}dx = \frac{2^{c+d+2}}{\Gamma(c+d-1)}. \tag{43}$$

One also can assume that the Pascal simplex is drawn in m-dimensional Euclidean space $\mathbb{E}^m$. It is easy to notice that counter-images of the function (21) lie in a $(m-1)$-dimensional hypersurface perpendicular to the vector $[1,1,\ldots,1]$, so calculation of the function $\mathcal{N}$ is simply connected with a projection of the space $\mathbb{E}^m$ onto the line determined by this vector. The same is true for the second function defined by the m-tuple $(-s,-s+1,\ldots,+s)$. Therefore number of spin-configuration with a given total magnetization M, for a given number of spins n, corresponds to a projection onto two-dimensional space spanned by the orthogonal vectors **N** and **M**. The 'extended' Pascal triangle is simply the projection of the Pascal simplex (for points with non-negative integer coordinates, dashed line in Figure 1 correspond to this projection). This also yields that points $\underline{K},\underline{K}'\in\mathbb{E}^m$ has the same value of $n=\mathbf{N}(\underline{K})=\mathbf{N}(\underline{K}')$ and $M=\mathbf{M}(\underline{K})=\mathbf{M}(\underline{K}')$ iff the vector $\underline{K}-\underline{K}'\in\mathbb{R}^m$ is orthogonal to both vectors **N** and **M**. For example, when $n=4$ and $s=3/2$ $(m=4)$ we have four orbits with $M=0$: (2,0,0,2), (1,1,1,1), (1,0,3,0), (0,3,0,1). This points (in $\mathbb{E}^4$) determines six vectors in $\mathbb{R}^4$: [1,-1,-1,1], [1,0,-3,2], [2,-3,0,1], [0,1,-2,1], [1,-2,1,0], [1,-3,3,-1]. These vectors are orthogonal to vectors [1,1,1,1] and [-3/2,-1/2,1/2,3/2] and th first and the sixth can be treated as the orthogonal basis in two-dimensional space complementary to the subspace containing extended Pascal triangle.

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