Realizability of a Model in Infinite Statistics

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Abstract. Following Greenberg and others, we study a space with a collection of operators $a(k)$ satisfying the "q-mutator relations" $a(l)a^\dagger(k) - qa^\dagger(k)a(l) = \delta_{k,l}$ (corresponding for $q = \pm 1$ to classical Bose and Fermi statistics). We show that the $n! \times n!$ matrix $A_n(q)$ representing the scalar products of n-particle states is positive definite for all n if q lies between -1 and $+1$, so that the commutator relations have a Hilbert space representation in this case (this has also been proved by Fivel and by Bożejko and Speicher). We also give an explicit factorization of $A_n(q)$ as a product of matrices of the form $(1 - q^j T)^{\pm 1}$ with $1 \le j \le n$ and T a permutation matrix. In particular, $A_n(q)$ is singular if and only if $q^M = 1$ for some integer M of the form $k^2 - k$, $2 \le k \le n$.

1. Introduction

In this paper we study the following object: a Hilbert space **H** together with a non-zero distinguished vector $|0\rangle$ (vacuum state) and a collection of operators a_k: **H** → **H** satisfying the commutation relations ("q-mutator relations")

$$a(l)\,a^\dagger(k) - q a^\dagger(k)\,a(l) = \delta_{k,l} \quad (\forall k, l) \tag{1}$$

and the relations

$$a(k)|0\rangle = 0 \quad (\forall k). \tag{2}$$

Here q is a fixed real number and $a^\dagger(l)$ denotes the adjoint of $a(l)$. The statistics based on the commutation relation (1) generalizes classical Bose and Fermi statistics, corresponding to $q = 1$ and $q = -1$, respectively, as well as the intermediate case $q = 0$ suggested by Hegstrom and investigated by Greenberg [1]. The study of the general case was inititated by Polyakov and Biedenharn [2].

Our first main result is a realizability theorem saying that the object just described exists if $-1 < q < 1$. In view of (2), we can think of the $a(k)$ as annihilation operators and the $a^\dagger(k)$ as creation operators. As well as the 0-particle state $|0\rangle$, our space must contain the many-particle states obtained by applying combinations of $a(k)$'s and $a^\dagger(k)$'s to $|0\rangle$. To prove the realizability of our model it is obviously necessary and sufficient to consider the minimal space

containing these vectors. We therefore define for each $q \in \mathbb{R}$ an inner product space $\mathbf{H}(q)$ generated by $|0\rangle$ and its images under polynomials in the operators $a(k)$ and $a^\dagger(k)$, subject to the relations (1) and (2). It has a basis consisting of n-particle states

$$\mathbf{x_k} = a^\dagger(k_1) \cdots a^\dagger(k_n)|0\rangle$$

for each $n \geq 0$ and each n-tuple of indices $\mathbf{k} = (k_1, \ldots, k_n)$, since we can use (1) to write any monomial in the $a(k)$'s and $a^\dagger(k)$'s as a sum of monomials having all the $a(k)$'s on the right and all the $a^\dagger(k)$'s on the left, and the only ones of these which do not annihilate $|0\rangle$ are those consisting of $a^\dagger(k)$'s only (the linear independence is clear). By the same argument, we can use (1) and (2) to calculate each scalar product $(\mathbf{x_l}, \mathbf{x_k})$ as a polynomial in q, for instance, for $k \neq l$ we have

$$(\mathbf{x}_{kl}, \mathbf{x}_{lk}) = \langle 0|a(l)\,a(k)\,a^\dagger(l)\,a^\dagger(k)|0\rangle = q\langle 0|a(l)\,a^\dagger(l)\,a(k)\,a^\dagger(k)|0\rangle$$
$$= q\langle 0|(1+qa^\dagger(l)\,a(l))\,(1+qa^\dagger(k)\,a(k))|0\rangle = q\langle 0|0\rangle = q\,.$$

(Here $\langle 0|$ denotes the operator $(|0\rangle, \cdot)$ and we have normalized by $\langle 0|0\rangle = 1$.) In particular, for each value of q the infinite matrix $A(q) = \{(x_l, x_k)\}_{l,k}$ is well-defined. The condition for the Hilbert space realizability of the q-mutator relation (1) is then that $A(q)$ be positive definite, i.e., that $(\mathbf{x}, \mathbf{x}) > 0$ for every non-zero vector $\mathbf{x} \in \mathbf{H}(q)$.

Theorem 1. *The matrix $A(q)$ is positive definite for $-1 < q < 1$, so that the q-mutator relation (1) has a Hilbert space realization for q in this range.*

It is easy to see that (x_k, x_l) vanishes unless $\mathbf{k}$ is a permutation of $\mathbf{l}$. Thus the space $\mathbf{H}(q)$ [respectively the matrix $A(q)$] is the direct sum of infinitely many finite-dimensional spaces (respectively matrices) indexed by all *unordered* n-tuples $\{k_1, \ldots, k_n\}$, and we only have to show the positive definiteness of these. We will show in Sect. 2 that the general case of this follows from the case when all of the indices k_i are distinct. It is not hard to see (Sect. 2) that

$$(\mathbf{x}_{\pi(1)\ldots\pi(n)}, \mathbf{x}_{1\ldots n}) = q^{I(\pi)} \tag{3}$$

for each permutation π in the nth symmetric group $\mathfrak{S}_n$, where $I(\pi)$ denotes the number of *inversions* of π, i.e., the number of $i, j \in [1, n]$ for which $i < j$ but $\pi(i) > \pi(j)$. Thus the problem reduces to showing that the $n! \times n!$ matrix $A_n = A_n(q)$ defined by

$$A_n(\pi, \sigma) = q^{I/\sigma^{-1}\pi)} \quad (\pi, \sigma \in \mathfrak{S}_n) \tag{4}$$

is positive definite for q between -1 and 1. For this, in turn, it is sufficient by continuity to show that $A_n(q)$ is non-singular in this range, since $A_n(0)$ is the identity matrix and the eigenvalues of $A_n(q)$ vary continuously with q and are real for q real (because $A_n(q)$ is real and symmetric). We will prove the following stronger statement.

Theorem 2. *The determinant of the matrix $A_n(q)$ is given by*

$$\det A_n(q) = \prod_{k=1}^{n-1} (1 - q^{k^2+k})^{\frac{n!\,(n-k)}{k^2+k}}\,. \tag{5}$$

In particular, $A_n(q)$ is non-singular for all complex numbers q except the Nth roots of unity for $N = 2, 6, 12, \ldots, n^2 - n$.

We will also describe explicitly the inverse of $A_n(q)$. Based on calculations for $n \leq 5$, we conjecture that

$$A_n(q)^{-1} \overset{?}{\in} \frac{1}{\Delta_n} M_{n!}(\mathbb{Z}[q]), \qquad \Delta_n := \prod_{k=1}^{n-1} (1 - q^{k^2+k}). \tag{6}$$

For instance, for $n = 3$ we have

$$A_3(q) = \begin{bmatrix} 1 & q & q & q^2 & q^2 & q^3 \\ q & 1 & q^2 & q & q^3 & q^2 \\ q & q^2 & 1 & q^3 & q & q^2 \\ q^2 & q & q^3 & 1 & q^2 & q \\ q^2 & q^3 & q & q^2 & 1 & q \\ q^3 & q^2 & q^2 & q & q & 1 \end{bmatrix}, \tag{7}$$

where the rows and columns are indexed by the elements of $\mathfrak{S}_3$ in the order [123], [213], [132], [231], [312], [321] (we use $[j_1 \ldots j_n]$ to denote the element π of $\mathfrak{S}_n$ defined by $\pi(i) = j_i$). The determinant of this matrix is $(1 - q^2)^6 (1 - q^6)$ and its inverse is

$$A_3(q)^{-1} = \Delta_3^{-1} \begin{bmatrix} 1+q^2 & -q & -q & -q^4 & -q^4 & q^3+q^5 \\ -q & 1+q^2 & -q^4 & -q & q^3+q^5 & -q^4 \\ -q & -q^4 & 1+q^2 & q^3+q^5 & -q & -q^4 \\ -q^4 & -q & q^3+q^5 & 1+q^2 & -q^4 & -q \\ -q^4 & q^3+q^5 & -q & -q^4 & 1+q^2 & -q \\ q^3+q^5 & -q^4 & -q^4 & -q & -q & 1+q^2 \end{bmatrix}. \tag{8}$$

Finally, we remark that the matrix $A_n(q)$ splits as a direct sum of pieces corresponding to the irreducible representations of $\mathfrak{S}_n$, the piece corresponding to a representation Π of dimension d being the direct sum of d copies of a $d \times d$ matrix $A_{n,\Pi}(q)$. For the bosonic and fermionic cases $q = 1$ and $q = -1$ all of these matrices are identically zero except for the one corresponding to the one-dimensional trivial or alternating representation, respectively, but for $-1 < q < 1$ Theorem 1 says that every representation of every symmetric group occurs in a non-trivial (indeed, non-degenerate) way. (This is the reason for the term "infinite statistics" used by the physicists.) It would be of interest to calculate the determinants of the matrices $A_{n,\Pi}(q)$, say in terms of the Young diagram corresponding to Π. By Theorem 2, each of these determinants is a product of cyclotomic polynomials $\Phi_m(q)$ for integers m dividing some $k^2 + k$, $1 \leq k \leq n - 1$.

The paper is organized as follows. In Sect. 2 we give some generalities on group determinants and show that Theorem 1 follows from Theorem 2, which is then proved in Sect. 3. In Sect. 4 we give an explicit description of the inverse matrix of $A_n(q)$, while Sect. 5 gives a conjectural formula for the "number operators" in the Hilbert space $\mathbf{H}(q)$.

The author would like to thank O. W. Greenberg who told him about the q-mutator relation and suggested the problem of proving the positive definiteness for $-1 < q < 1$. This positive definiteness has been proved independently by Fivel and by Bożejko and Speicher [3]. (However, Fivel apparently asserts that the zeros of $A_n(q)$ are all roots of $q^{2n} = 1$, which contradicts Theorem 2 and is false for all

$n \geq 4$.) Consequences and related results are discussed in several subsequent papers by Greenberg [4].

2. Group Determinants and the Reduction to $A_n(q)$

Let G be a finite group of order m and $\varrho: G \to GL(V)$ a representation of G on a (finite-dimensional) complex vector space V. We can extend ϱ to an algebra homomorphism from the group algebra

$$\mathbb{C}[G] = \left\{ \sum_{g \in G} t_g g \mid t_g \in \mathbb{C} \text{ for } g \in G \right\}$$

to the matrix algebra $\mathrm{End}(V)$ by $\varrho(\sum t_g g) = \sum t_g \varrho(g)$. The determinant of $\varrho(\sum t_g g)$ is a polynomial $F_\varrho(\mathbf{t})$ of degree $\dim(V)$ in the m variables $\mathbf{t} = \{t_g\}_{g \in G}$ which is determined by and uniquely determines the isomorphism class of the representation ϱ. Thus the entire representation theory of G can be expressed in terms of the "group determinants" $F_\varrho(\mathbf{t})$; this is in fact the way that representation theory was developed in its early years (see for instance Weber's *Lehrbuch der Algebra*, Vol. 2, Chap. 7).

If V is reducible, say $V = V_1 \oplus V_2$, then $F_\varrho(\mathbf{t})$ splits as $F_{\varrho_1}(\mathbf{t}) F_{\varrho_2}(\mathbf{t})$, so the study of group determinants can be reduced to the case of irreducible representations of G. At the other extreme, let (V, R) be the *(right) regular representation* of G, i.e. $V = \mathbb{C}^G$ is the m-dimensional vector space of functions $f: G \to \mathbb{C}$ and $\varrho = R$ is given by

$$(R(g)f)(g') = f(g'g) \quad (g, g' \in G).$$

The matrix representation of R with respect to the basis of δ-functions on G is clearly given by

$$R(g)_{g_1, g_2} = \begin{cases} 1 & \text{if } g_1 g = g_2, \\ 0 & \text{otherwise}, \end{cases}$$

so that the group determinant $F_R(\mathbf{t})$ is the determinant of the $m \times m$ matrix $(t_{g_1^{-1} g_2})_{g_1, g_2 \in G}$. It is well known that R contains every irreducible representation Π of G with positive multiplicity (equal to $\dim \Pi$). Hence if $F_R(\mathbf{t}) \neq 0$ for some $\mathbf{t} \in \mathbb{C}^m$ then $F_\Pi(\mathbf{t}) \neq 0$ for every irreducible representation π and consequently $F_\varrho(\mathbf{t}) \neq 0$ for every representation ϱ of G. ──

Now apply this to $G = \mathfrak{S}_n$, $m = n!$. Formula (4) and the discussion just given say that $A_n = A_n(q)$ is just the matrix representation $R(\alpha_n)$ of the element

$$\alpha_n = \alpha_n(q) = \sum_{\pi \in \mathfrak{S}_n} q^{I(\pi)} \pi \in \mathbb{C}[\mathfrak{S}_n] \tag{9}$$

acting on the regular representation $(\mathbb{C}^{\mathfrak{S}_n}, R)$. Here we are thinking of q as being a complex number; if q is thought of as a variable, then $\alpha_n(q)$ belongs to the group ring $\mathbb{Z}[q][\mathfrak{S}_n]$. We will usually consider q as fixed and omit it from the notation. To prove Theorems 1 and 2, we will forget that α_n is acting on $\mathbb{C}^{\mathfrak{S}_n}$ and simply show that it is invertible in the group algebra if $\prod_{i=1}^{n-1}(1 - q^{k^2+k}) \neq 0$, in which case the inverse of the matrix A_n is simply the matrix $R(\alpha_n^{-1})$.

We now use this point of view to show how the positive definiteness of $A(q) = \{(\mathbf{x}_l, \mathbf{x}_k)\}$ follows from that of the $n! \times n!$ matrices $A_n(q)$ for $n = 1, 2, 3, \ldots$. Equation (1) gives by induction the formula for any indices $l, k_1, \ldots, k_n$ (not

necessarily distinct)

$$a(l)\,a^\dagger(k_1) \cdots a^\dagger(k_n) = q^n a^\dagger(k_1) \cdots a^\dagger(k_n)\,a(l)$$
$$+ \sum_{\substack{1 \leq i \leq n \\ k_i = l}} q^{i-1} a^\dagger(k_1) \cdots \widehat{a^\dagger(k_i)} \cdots a^\dagger(k_n),$$

where the sum runs over those indices i for which k_i equals l and the hat over the ith term of the product indicates that this term is to be omitted. Combining this with (2) gives

$$a(l)\,a^\dagger(k_1) \cdots a^\dagger(k_n)|0\rangle = \sum_{\substack{1 \leq i \leq n \\ k_i = l}} q^{i-1} a^\dagger(k_1) \cdots \widehat{a^\dagger(k_i)} \cdots a^\dagger(k_n)|0\rangle.$$

Now induction on m gives a formula for $a(l_m) \cdots a(l_1)\,a^\dagger(k_1) \cdots a^\dagger(k_n)|0\rangle$ as a sum of terms $q^N a^\dagger(k_1) \cdots \widehat{a^\dagger(k_{i_1})} \cdots \widehat{a^\dagger(k_{i_m})} \cdots a^\dagger(k_n)|0\rangle$, where $i_1, \ldots, i_m$ are distinct indices with $k_{i_1}, \ldots, k_{i_m}$ equal to $l_1, \ldots, l_m$ in some order, the final result for $m = n$ being

$$a(l_n) \cdots a(l_1)\,a^\dagger(k_1) \cdots a^\dagger(k_n)|0\rangle = \sum_{\substack{1 \leq i_1, \ldots, i_n \leq n \\ i_1, \ldots, i_n \text{ distinct} \\ k_{i_1} = l_1, \ldots, k_{i_n} = l_n}} q^{\#\{1 \leq r < s \leq n,\ i_r > i_s\}}|0\rangle,$$

i.e., in the notation of Sect. 1,

$$(\mathbf{x}_l, \mathbf{x}_k) = \langle 0|\,a(l_n) \cdots a(l_1)\,a^\dagger(k_1) \cdots a^\dagger(k_n)|0\rangle = \sum_{\substack{\pi \in \mathfrak{S}_n \\ l_i = k_{\pi(i)}\,(i = 1, \ldots, n)}} q^{I(\pi)}. \quad (10)$$

This formula includes (4) and also shows that $(\mathbf{x}_l, \mathbf{x}_k) = 0$ unless $\mathbf{l}$ and $\mathbf{k}$ are permutations of one another, as already mentioned in Sect. 1, so that $A(q)$ splits up into the matrices $A_{\mathbf{k}_0}$ having as entries the numbers $(\mathbf{x}_l, \mathbf{x}_k)$ for $\mathbf{l}$ and $\mathbf{k}$ ranging over all permutations of a given index set $\mathbf{k}_0$, e.g. for $\mathbf{k}_0 = (k, k, l)$ with $k \neq l$

$$A_{\mathbf{k}_0} = \begin{pmatrix} (\mathbf{x}_{kkl}, \mathbf{x}_{kkl}) & (\mathbf{x}_{kkl}, \mathbf{x}_{klk}) & (\mathbf{x}_{kkl}, \mathbf{x}_{lkk}) \\ (\mathbf{x}_{klk}, \mathbf{x}_{kkl}) & (\mathbf{x}_{klk}, \mathbf{x}_{klk}) & (\mathbf{x}_{klk}, \mathbf{x}_{lkk}) \\ (\mathbf{x}_{lkk}, \mathbf{x}_{kkl}) & (\mathbf{x}_{lkk}, \mathbf{x}_{klk}) & (\mathbf{x}_{lkk}, \mathbf{x}_{lkk}) \end{pmatrix}$$

$$= \begin{pmatrix} 1+q & q+q^2 & q^2+q^3 \\ q+q^2 & 1+q^3 & q+q^2 \\ q^2+q^3 & q+q^2 & 1+q \end{pmatrix}.$$

In each such matrix, the rows and columns are indexed by the permutations $\mathbf{k} = \pi\mathbf{k}_0$ of $\mathbf{k}_0$ or equivalently by the left cosets G/H, where $G = \mathfrak{S}_n$ and H is the subgroup of permutations of $\mathfrak{S}_n$ fixing $\mathbf{k}_0$. Write $\mathbf{k} = \sigma\mathbf{k}_0$, $\mathbf{l} = \tau\mathbf{k}_0$ with $\sigma, \tau \in \mathfrak{S}_n$; then (10) says that the $(\mathbf{l}, \mathbf{k})$ matrix coefficient of $A_{\mathbf{k}_0}$ is equal to

$$\sum_{\substack{\pi \in \mathfrak{S}_n \\ \pi\sigma H = \tau H}} q^{I(\pi)}.$$

But a moment's thought shows that this is simply the $(\tau H, \sigma H)$-matrix coefficient (with respect to the basis of δ-functions) of the element

$$\alpha_n = \sum_\pi q^{I(\pi)}\pi$$

on the subspace $V = \mathbf{C}^{G/H}$ of $\mathbf{C}^G$ consisting of functions $f: G \to \mathbf{C}$ which satisfy $f(gh) = f(g)$ for all $g \in G$, $h \in H$. This subspace is invariant under the action R of G on $\mathbf{C}^G$, so that (V, R) is a representation of G. Hence if α_n is invertible in the group algebra $\mathbf{C}[G]$, then the matrix A_{k_0} is invertible. This completes the reduction of Theorem 1 to Theorem 2.

3. Factorization of α_n; Proof of Theorem 2

We first introduce some notations. As in Sect. 1 we denote by $[i_1, i_2, \ldots, i_n]$ the permutation in $\mathfrak{S}_n$ which sends 1 to i_1, 2 to i_2, ..., n to i_n. We identify $\mathfrak{S}_{n-1}$ with the subgroup of $\mathfrak{S}_n$ consisting of permutations fixing n. For $1 \leq k \leq n$ we denote by $T_{k,n}$ the element $[1, \ldots, k-1, n, k, k+1, \ldots, n-1]$ of $\mathfrak{S}_n$, i.e.

$$T_{k,n}(i) = \begin{cases} i & 1 \leq i < k, \\ n & i = k, \\ i-1 & k < i \leq n, \end{cases} \qquad T_{k,n}^{-1}(i) = \begin{cases} i & 1 \leq i < k, \\ i+1 & k \leq i < n, \\ k & i = n. \end{cases}$$

Any element $\pi \in \mathfrak{S}_n$ can be represented uniquely as $\sigma T_{k,n}$ with $\sigma \in \mathfrak{S}_{n-1}$ and $1 \leq k \leq n$ (namely $k = \pi^{-1}(n)$, $\sigma = \pi T_{k,n}^{-1}$), and a short calculation shows that then $I(\pi)$ equals $I(\sigma) + n - k$. Hence

$$\alpha_n = \sum_{\pi \in \mathfrak{S}_n} q^{I(\pi)} \pi = \sum_{\substack{\sigma \in \mathfrak{S}_{n-1} \\ 1 \leq k \leq n}} q^{I(\sigma T_{k,n})} \sigma T_{n,k} = \left(\sum_{\sigma \in \mathfrak{S}_{n-1}} q^{I(\sigma)} \sigma \right) \left(\sum_{k=1}^{n} q^{n-k} T_{k,n} \right).$$

In other words,

Proposition 1. *Define* $\beta_n = \beta_n(q) = \sum_{k=1}^{n} q^{n-k} T_{k,n} \in \mathbf{C}[\mathfrak{S}_n]$. *Then* $\alpha_n = \alpha_{n-1} \beta_n$.

Here α_{n-1} is considered as an element of $\mathbf{C}[\mathfrak{S}_n]$ via the inclusion $\mathfrak{S}_{n-1} \subset \mathfrak{S}_n$. In particular, the representation of α_{n-1} in R_n, the $n!$-dimensional regular representation of $\mathfrak{S}_n$, consists of n copies of the representation of α_{n-1} in R_{n-1}. Thus in terms of the matrices A_n we can rewrite Proposition 1 as $A_n = (A_{n-1} \otimes 1_n) \cdot B_n$, where $A_{n-1} \otimes 1_n$ denotes the $n! \times n!$ block matrix with n copies of A_{n-1} on the diagonal blocks and zeros elsewhere and $B_n = B_n(q)$ has the matrix coefficients

$$B_n(\pi, \sigma) = \begin{cases} q^{n-k} & \text{if } \pi\sigma^{-1} = T_{k,n} \text{ for some } 1 \leq k \leq n, \\ 0 & \text{otherwise}. \end{cases}$$

In particular, $\det(A_n(q)) = \det(A_{n-1}(q))^n \det(B_n(q))$, so by induction on n we have reduced Theorem 2 to the simpler

Theorem 2'. $\det(B_n(q)) = \prod_{i=1}^{n-1} (1 - q^{k^2+k})^{\frac{n!}{k^2+k}}$.

We now make a second reduction by expressing B_n in turn as a product of yet simpler matrices.

Proposition 2. *For each* n *define elements* γ_n, δ_n *in the group algebra* $\mathbf{C}[\mathfrak{S}_n]$ *by*

$$\gamma_n = (1 - q^{n-1} T_{1,n})(1 - q^{n-2} T_{2,n}) \cdots (1 - q T_{n-1,n}),$$
$$\delta_n = (1 - q^{n+1} T_{1,n})(1 - q^n T_{2,n}) \cdots (1 - q^2 T_{n,n}).$$

Then $\beta_n \gamma_n = \delta_{n-1}$.

Proof. Let $\beta_{r,n} = \sum_{k=r}^{n} q^{n-k} T_{k,n}$, so that $\beta_{1,n} = \beta_n, \beta_{n,n} = 1$ (note that $T_{n,n} = 1 \in \mathfrak{S}_n$).
Using the easily checked commutation relation

$$T_{k,n} T_{r,n} = T_{r,n-1} T_{k+1,n} \quad (r \leq k \leq n-1),$$

we find

$$\beta_{r,n} \cdot (1 - q^{n-r} T_{r,n}) = \sum_{k=r+1}^{n} q^{n-k} T_{k,n} + q^{n-r} T_{r,n}$$

$$- q^{n-r} T_{r,n} - \sum_{k=r}^{n-1} q^{2n-k-r} T_{k,n} T_{r,n}$$

$$= \sum_{k=r+1}^{n} q^{n-k} T_{k,n} - \sum_{k=r+1}^{n} q^{2n-k+1-r} T_{r,n-1} T_{k,n}$$

$$= (1 - q^{n-r+1} T_{r,n-1}) \cdot \beta_{r+1,n}$$

and hence by induction on r (starting with the trivial case $r = 0$)

$$\beta_{1,n}(1 - q^{n-1} T_{1,n}) \cdots (1 - q^{n-r} T_{r,n})$$
$$= (1 - q^n T_{1,n-1}) \cdots (1 - q^{n+1-r} T_{r,n-1}) \beta_{r+1,n}.$$

The case $r = n - 1$ of this identity is the desired identity. □

To complete the proof of Theorem 2 we need to compute the determinants of the factors in γ_n and δ_{n-1} under the regular representation R_n of $\mathfrak{S}_n$. We use the inclusions $\mathfrak{S}_b \subset \mathfrak{S}_{b+1} \subset \cdots \subset \mathfrak{S}_n$ to define elements $T_{a,b} \in \mathfrak{S}_n$ for all $1 \leq a \leq b \leq n$ (we actually need only the cases $b = n - 1$ and n). Its characteristic polynomial is given by:

Lemma. *For* $1 \leq a \leq b \leq n$ *the determinant of* $R_n(1 - t T_{a,b})$ *is* $(1 - t^{b-a+1})^{\frac{n!}{b-a+1}}$.

Proof. The element $T_{a,b} \in \mathfrak{S}_n$ is a cyclic permutation of the indices $a, a+1, \ldots, b$ and hence has order $b - a + 1$. But if G is an arbitrary finite group of order m and $g \in G$ an element of order d, then the characteristic polynomial $\det(1 - t R(g))$ of g under the regular representation is $(1 - t^d)^{m/d}$, because the cycle structure of the permutation of G given by left multiplication by g^{-1} consists of m/d disjoint cycles of length d. The lemma follows. □

The proof of Theorem 2 is now immediate: we have

$$\det(R_n(\gamma_n)) = \prod_{k=1}^{n-1} \det(R_n(1 - q^k T_{n-k,n})) = \prod_{k=1}^{n-1} (1 - q^{k(k+1)})^{\frac{n!}{k+1}},$$

$$\det(R_n(\delta_n)) = \prod_{k=1}^{n} \det(R_n(1 - q^{k+1} T_{n-k+1,n})) = \prod_{k=1}^{n} (1 - q^{k(k+1)})^{\frac{n!}{k}},$$

and hence

$$\det(B_n) = \det(R_n(\beta_n)) = \frac{\det(R_n(\delta_{n-1}))}{\det(R_n(\gamma_n))} = \frac{\det(R_{n-1}(\delta_{n-1}))^n}{\det(R_n(\gamma_n))}$$

$$= \prod_{k=1}^{n-1} (1 - q^{k(k+1)})^{\frac{n\cdot(n-1)!}{k} - \frac{n!}{k+1}}$$

$$= \prod_{k=1}^{n-1} (1 - q^{k(k+1)})^{\frac{n!}{k(k+1)}},$$

which is Theorem 2'; Theorem 2 then follows by induction from this and Proposition 1.

4. Formula for $A_n(q)^{-1}$

According to Propositions 1 and 2 we have

$$\beta_n = \delta_{n-1}\gamma_n^{-1},$$

$$\alpha_n = \beta_2 \cdots \beta_n = \delta_1\gamma_2^{-1}\delta_2\gamma_3^{-1} \cdots \gamma_{n-1}^{-1}\delta_{n-1}\gamma_n^{-1}$$

and hence

$$\alpha_n^{-1} = \gamma_n\delta_{n-1}^{-1}\gamma_{n-1} \cdots \gamma_2\delta_1^{-1}.$$

To invert α_n, therefore, the first step is to invert δ_k for each k.

Proposition 3. *For $\pi \in \mathfrak{S}_n$ define $W(\pi) \in \mathbb{Z}$ by*

$$W(\pi) = \sum_{\substack{1 \leq i < j \leq n \\ \pi(i) > \pi(j)}} (1 + (n+1-i)(n+1-j)\delta_{j-1,i})$$

$$= I(\pi) + \sum_{\substack{1 \leq i \leq n-1 \\ \pi(i+1) < \pi(i)}} (n+1-i)(n-i)$$

and set $\varepsilon_n = \sum_{\pi \in \mathfrak{S}_n} q^{W(\pi)}\pi^{-1} \in \mathfrak{S}_n$. Then $\delta_n^{-1} = \dfrac{1}{\Lambda_{n+1}}\varepsilon_n$ with Λ_{n+1} as in Eq. (6).

Proof. Denote by $\sigma \mapsto \tilde{\sigma}$ the map $\mathfrak{S}_{n-1} \to \mathfrak{S}_n$ defined by $\tilde{\sigma}(1) = 1$, $\tilde{\sigma}(i) = \sigma(i-1) + 1$ for $i > 1$ (this is a homomorphism since $\tilde{\sigma}$ is just $T_{1,n}^{-1}\sigma T_{1,n}$). Then $\tilde{T}_{a,b} = T_{a+1,b+1}$ for $1 \leq a < b \leq n-1$, so $\delta_n = (1 - q^{n+1}T_{1,n})\tilde{\delta}_{n-1}$. Hence by induction it suffices to show that $\varepsilon_n(1 - q^{n+1}T_{1,n}) = (1 - q^{n^2+n})\tilde{\varepsilon}_{n-1}$.

For $\pi \in \mathfrak{S}_n$, let $k = \pi^{-1}(1)$ and denote by π' the element $T_{1,n}\pi$ of $\mathfrak{S}_n$. Since $\pi'(k) = n$ but $\pi'(i) = \pi(i) - 1$ for all $i \neq k$, all the terms in the definition of $W(\pi)$ and of $W(\pi')$ are the same except those with i or j equal to k, so

$$W(\pi') - W(\pi) = \sum_{k < j \leqq n} (1 + (n+1-k)(n+1-j)\delta_{j,k+1})$$

$$- \sum_{1 \leqq i < k} (1 + (n+1-i)(n+1-k)\delta_{i,k-1})$$

$$= n - k + (n+1-k)(n-k) - (k-1)$$

$$- \begin{cases} (n+1-k)(n+2-k) & \text{if } k > 1 \\ 0 & \text{if } k = 1 \end{cases}$$

$$= \begin{cases} -n-1 & \text{if } k \neq 1, \\ n^2 - 1 & \text{if } k = 1. \end{cases}$$

Hence

$$\varepsilon_n(1 - q^{n+1}T_{1,n}) = \sum_{\pi \in \mathfrak{S}_n} (q^{W(\pi)} - q^{W(T_{1,n}\pi)+n+1})\pi^{-1}$$

$$= \sum_{\substack{\pi \in \mathfrak{S}_n \\ \pi(1)=1}} (q^{W(\pi)} - q^{W(\pi)+n^2+n})\pi^{-1}$$

$$= (1 - q^{n^2+n}) \sum_{\sigma \in \mathfrak{S}_{n-1}} q^{W(\sigma)}\tilde{\sigma}^{-1}$$

as desired. $\square$

We next give a formula expressing γ_n as a sum rather than a product.

Proposition 4. *The element* $\gamma_n \in \mathfrak{S}_n$ *defined in Proposition 2 is given by*

$$\gamma_n = \sum_{k=1}^{n} \gamma_{n,k}, \qquad \gamma_{n,k} = (-1)^{n-k} \sum_{\pi \in \mathfrak{S}_{n,k}} q^{I(\pi)}\pi^{-1},$$

where $\mathfrak{S}_{n,k}$ *is the subset of* $\mathfrak{S}_n$ *of cardinality* $\binom{n-1}{k-1}$ *consisting of those permutations* π *for which* $\pi(1) < \cdots < \pi(k) > \cdots > \pi(n)$.

Proof. Multiplying out the terms in the product defining γ_n, we find

$$\gamma_n = \sum_{s=0}^{n-1} (-1)^s \sum_{1 \leqq i_1 < \ldots < i_s \leqq n-1} q^{(n-i_1) + \cdots + (n-i_s)} T_{i_1,n} T_{i_2,n} \cdots T_{i_s,n}.$$

The element $\sigma = T_{i_1,n} T_{i_2,n} \cdots T_{i_s,n}$ of $\mathfrak{S}_n$ maps i_1 to n, i_2 to $n-1$, ..., and i_s to $n - s + 1$, and maps the rest of $\{1, 2, \ldots, n\}$ monotone increasingly to $\{1, 2, \ldots, n-s\}$. Moreover, it is easy to check that $(n - i_1) + \cdots + (n - i_s)$ equals $I(\sigma)$. The proposition now follows on setting $\pi = \sigma^{-1}$ and $k = n - s$. $\square$

The explicit formulas for δ_n^{-1} and γ_n just given together with the formula $\alpha_n^{-1} = \gamma_n \delta_{n-1}^{-1} \alpha_{n-1}^{-1}$ give an inductive method to calculate α_n for each n. To describe this a little more explicitly, we define another element of $\mathbb{C}[\mathfrak{S}_n]$ by

$$\zeta_n = \varepsilon_n \alpha_n^{-1}$$

with ε_n as in Proposition 3. We conjecture that ζ_n has coefficients which are polynomials in q. Propositions 1–3 give $\alpha_n^{-1} = \Delta_n^{-1}\gamma_n\zeta_{n-1}$, so this conjecture implies the conjecture in (6). In fact, the two propositions are equivalent. Indeed, for each $\pi \in \mathfrak{S}_{n,k}$ we have $\pi(k) = n$ and hence $\pi = \sigma T_{n,k}$ for some $\sigma \in \mathfrak{S}_{n-1}$, so $\gamma_{n,k}$

equals $T_{n,k}^{-1} \gamma_{n-1,k}^{*}$ with $\gamma_{n-1,k}^{*} \in \mathbb{C}[\mathfrak{S}_{n-1}]$ (in fact $\gamma_{n-1,k}^{*} = \gamma_{n-1,k-1} - \gamma_{n-1,k}$). It follows that if π is any element of $\mathfrak{S}_{n}$, and $\pi = \sigma T_{n,k}(1 \leq k \leq n,\ \sigma \in \mathfrak{S}_{n-1})$ its canonical decomposition as at the beginning of Sect. 3, then the coefficient of π in $\Delta_{n}\alpha_{n}^{-1}$ equals the coefficient of σ^{-1} in $\gamma_{n-1,k}^{*}\zeta_{n-1}$. In particular, taking $k = n$ we find that the first $(n-1)!$ coefficients in $\Delta_{n}\alpha_{n}^{-1}$ are exactly the coefficients of ζ_{n-1}, so that the integrality of $\Delta_{n}\alpha_{n}$ implies that of ζ_{n-1} for each n.

We illustrate with numerical examples for $n \leq 4$. For $n = 2$ we have

$$\alpha_{2} = 1 + qT_{1,2}, \qquad \alpha_{2}^{-1} = \frac{1}{1-q^{2}}(1 - qT_{1,2}), \qquad \varepsilon_{2} = 1 + q^{3}T_{1,2},$$

$$\zeta_{2} = \varepsilon_{2}\alpha_{2}^{-1} = (1 + q^{2}) - qT_{1,2}.$$

We see that ζ_{2} is integral and that its coefficients are the first two coefficients of $\Delta_{3}\alpha_{3}^{-1}$, i.e., the first two coefficients of the matrix in (8). The other coefficients of α_{3}^{-1} are obtained by multiplying ζ_{2} by the elements $\gamma_{2,k}^{*}$ for $k = 2$ and $k = 3$, and we find

$$(1 - q^{2})(1 - q^{6})\alpha_{3}^{-1} = (1 - T_{2,3}^{-1}(qT_{1,3} + q^{2}T_{2,3}) + T_{1,3}^{-1}(q^{3}T_{1,3}T_{2,3}))\zeta_{2}$$
$$= (1 + q^{2})[123] - q[213] - q[132] - q^{4}[231]$$
$$- q^{4}[312] + (q^{3} + q^{5})[321],$$

giving the remaining coefficients in the first row of the matrix in (8) (the other rows are permutations of the first one). Write this as $\Delta_{3}\alpha_{3}^{-1} = \{1 + q^{2}, -q, -q, -q^{4}, -q^{4}, q^{3} + q^{5}\}$ in the obvious notation. Using this value of α_{3}^{-1} and the value $\varepsilon_{3} = \{1,\ q^{7},\ q^{3},\ q^{4},\ q^{8},\ q^{11}\}$ we find $\zeta_{3} = \{1 + 2q^{2} + q^{4} + 2q^{6} + q^{8}, -q - q^{3} - q^{5} - q^{7}, -q - q^{7}, -q^{4}, -q^{4}, q^{3} + q^{5}\}$, which is integral as claimed. Now multiplying this by the various components $\gamma_{4,k}(1 \leq k \leq 4)$, we find

$$\alpha_{4}^{-1} = (1 - q^{2})^{-1}(1 - q^{6})^{-1}(1 - q^{12})^{-1}$$
$$\times \{1 + 2q^{2} + q^{4} + 2q^{6} + q^{8}, -q - q^{3} - q^{5} - q^{7}, -q - q^{7}, -q^{4}, -q^{4}, q^{3} + q^{5};$$
$$-q - q^{3} - q^{5} - q^{7}, q^{2} + q^{4} + q^{6}, -q^{4}, -q^{9} - q^{11}, 0, q^{10};$$
$$-q^{4}, 0, q^{3} + q^{5}, q^{10}, -q^{8} - q^{10} - q^{12}, q^{7} + q^{9} + q^{11} + q^{13};$$
$$-q^{9} - q^{11}, q^{10}, q^{10}, q^{7} + q^{13}, q^{7} + q^{9} + q^{11} + q^{13},$$
$$-q^{6} - 2q^{8} - q^{10} - 2q^{12} - q^{14}\},$$

where the 24 components have been listed in the obvious order (namely, the elements $\sigma \in \mathfrak{S}_{3}$ in the order above, followed by the elements $T_{3,4}\sigma$ with the same σ, then the $T_{2,4}\sigma$, then $T_{1,4}\sigma$). This gives the 24 elements of the first row of the matrix $A_{4}(q)^{-1}$, the other rows of course being permutations of this one. We have also checked the ζ_{4} has integral coefficients and thus that (6) holds for $n = 5$.

5. Number Operators

For each index k, the kth *number operator* is the operator on $\mathbf{H}$ having each vector $\mathbf{x}_{k} = a^{\dagger}(k_{1}) \cdots a^{\dagger}(k_{n})|0\rangle$ as an eigenvector with eigenvalue equal to the number of i with $k_{i} = k$, so that the eigenspace of $N(k)$ with eigenvalue r is the space spanned

by the states containing exactly r particles of type k. It is easy to see that this definition is equivalent to the requirements

$$N^\dagger(k) = N(k), \quad N(k)|0\rangle = 0, \quad [N(k), a^\dagger(l)] = \delta_{kl} a^\dagger(l) \quad \text{for all } l \quad (11)$$

(and hence $[N(k), a(l)] = -\delta_{kl} a(l)$ for all l).

Consider first the case in which there is only one operator $a(1)$ and its adjoint, i.e., only one kind of particle. In this case $\mathbf{H}(q)$ can be realized explicitly as the space spanned by vectors $e_0 = |0\rangle, e_1, e_2, \ldots$ with

$$a(1)e_n = \sqrt{n \frac{1-q^n}{1-q}}\, e_{n-1} \quad (=0 \text{ for } n=0), \quad a^\dagger(1)e_n = \sqrt{\frac{1}{n+1} \frac{1-q^{n+1}}{1-q}}\, e_{n+1},$$

since then

$$a(1)\, a^\dagger(1)\, e_n - q\, a^\dagger(1)\, a(1)\, e_n = \frac{1-q^{n+1}}{1-q}\, e_n - q\, \frac{1-q^n}{1-q}\, e_n = e_n,$$

while the number operator $N(1)$ is given by either of the two formulas [5]

$$N(1) = \sum_{n=1}^{\infty} \frac{(1-q)^n}{1-q^n}\, a^\dagger(1)^n\, a(1)^n = \sum_{n=1}^{\infty} \frac{(1-q)^n}{\log(1/q^n)}\, (a^\dagger(1)\, a(1))^n, \quad (12)$$

as one sees either by computing the action of the expressions on the right on the vectors e_n or else by verifying the relations (11) using (1) and (2). The first formula makes sense for all q between -1 and 1, the second (which can be rewritten $\dfrac{1-q^{N(1)}}{1-q} = a^\dagger(1)\, a(1)$) only for $0 < q < 1$. Both reduce to $N(1) = a^\dagger(1)\, a(1)$ in the limit as q tends to 1. For $q = 0$ the first formula reduces to

$$N(1) = \sum_{n=1}^{\infty} a^\dagger(1)^n\, a(1)^n \quad (q=0), \quad (13)$$

which makes sense since only finitely many of the terms act non-trivially on any given state.

In [1], Greenberg showed that the generalization of (13) to the case when there are many indices k is

$$N(k) = \sum_{n=1}^{\infty} \sum_{k_2, \ldots, k_n} a^\dagger(k_n) \cdots a^\dagger(k_2)\, a^\dagger(k)\, a(k)\, a(k_2) \cdots a(k_n) \quad (q=0).$$

We now give a conjectural generalization of this formula to the case of arbitrary q between -1 and 1. It is convenient to express the formula for all $N(k)$ simultaneously by giving a formula for the energy operator $\mathscr{E} = \sum_k E_k N(k)$, where the E_k (interpreted as the energy of particle k) are scalar coefficients.

Conjecture. *The operator $\mathscr{E}$ is given by*

$$\mathscr{E} = \sum_{n=1}^{\infty} \sum_{k_1, \ldots, k_n} \sum_{\pi \in \mathfrak{S}_n} \sum_{i=1}^{n} c_i(q, \pi) E_{k_i}\, a^\dagger(k_{\pi(n)}) \cdots a^\dagger(k_{\pi(1)})\, a(k_1) \cdots a(k_n),$$

where the coefficients $c_i(q, \pi)$ are given by

$$\sum_{\substack{\pi \in \mathfrak{S}_n \\ 1 \leq i \leq n}} c_i(q, \pi) X^{i-1} \pi = \alpha_n^{-1} (1 - qXT_{1,2}) (1 - q^2 XT_{1,3})$$

$$\cdots (1 - q^{n-1} XT_{1,n}) \in \mathbb{C}[X][\mathfrak{S}_n].$$

This formula gives the correct result up to terms annihilating all 1-, 2-, and 3-particle states, viz:

$$\mathscr{E} = \sum_k E_k a^\dagger(k) a(k)$$

$$+ \frac{1}{1 - q^2} \sum_{k,l} \left\{ (E_k + q^2 E_l) a^\dagger(l) a^\dagger(k) - q(E_k + E_l) a^\dagger(k) a^\dagger(l) \right\} a(k) a(l)$$

$$+ \frac{1}{(1 - q^2)(1 - q^6)} \times$$

$$\sum_{k,l,m} \left\{ ((1 + q^2) E_k + (q^2 + q^6) E_l + (q^6 + q^8) E_m) a^\dagger(m) a^\dagger(l) a^\dagger(k) \right.$$

$$- q(E_k + E_l + q^6 E_m) a^\dagger(m) a^\dagger(k) a^\dagger(l)$$

$$- q(E_k + q^6 (E_l + E_m)) a^\dagger(l) a^\dagger(m) a^\dagger(k)$$

$$- q^4 (E_k + E_l + E_m) a^\dagger(k) a^\dagger(m) a^\dagger(l)$$

$$- q^4 (E_k + E_l + E_m) a^\dagger(l) a^\dagger(k) a^\dagger(m)$$

$$\left. + q^3 (1 + q^2) (E_k + E_l + E_m) a^\dagger(k) a^\dagger(l) a^\dagger(m) \right\} a(k) a(l) a(m)$$

$$+ \cdots$$

Note added in proof. The conjecture stated in this section has now been proved by Sonia Stanciu (see paper following this one).

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