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Quantum Hall States and Boson Triplet Condensate for Rotating Spin-1 Bosons

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We propose and analyze two series of clustered quantum Hall states for rotating systems of spin-1 bosons. The first series [labeled SU(4)k] includes the exact ground states of a model Hamiltonian at large angular momentum L, and also for N = 3k particles at L = N. The latter is a spin-singlet boson-triplet condensate. The second series, labeled SO(5)k, includes exact ground states at large L for different parameter values.

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In the phenomenon of Bose-Einstein condensation (BEC) of cold atoms, the possibility of using bosons with internal degrees of freedom (spin 1 in particular) and of rotating the condensate has led to fascinating new possibilities for the states of matter that can be formed and observed. A multicomponent BEC can be realized by trapping higher spin atoms such as ⁸⁷Rb [1] and ²³Na [2] in optical traps, which do not affect the spin degeneracy, and spin-1 or “vector” BEC’s have been realized and studied [2,3]. In a model description, the two-body interactions of spin-1 or “vector” BEC’s have been realized and studied [2,3]. In a model description, the two-body interactions of spin-1 bosons are written as δ(r₁ - r₂)[c₀ + c₂S₁ · S₂], with c₀ = (g₀ + 2g₂)/3, c₂ = (g₂ - g₀)/3, and gₜ = 4πℏ²aₜ/Mₜ, with Mₜ the boson mass and aₜ the s-wave scattering length in the total spin S channel [4,5]. In the case of ²³Na one has c₂ > 0 and, hence, “antiferromagnetic” spin correlations. The “polar” ground state [4,5] has (S) = 0; it supports many interesting collective excitations (see [6] for a review). The case of ⁸⁷Rb has c₂ < 0, leading to a spin-polarized (ferromagnetic) ground state.

The effect of rotating a “scalar” BEC of spinless or spin-polarized atoms in an isotropic harmonic trap of frequency ω₀ can be studied at mean field level (the Gross-Pitaevskii equation), and a vortex lattice is found in a rotating system of spin-1 bosons. The effect of rotating a “vector” BEC of spinless or spin-polarized atoms in an isotropic harmonic trap of frequency ω₀ can be studied at mean field level (the Gross-Pitaevskii equation), and a vortex lattice is found in a rotating system of spin-1 bosons. The case of ²³Na one has c₂ > 0 and, hence, “antiferromagnetic” spin correlations. The “polar” ground state [4,5] has (S) = 0; it supports many interesting collective excitations (see [6] for a review). The case of ⁸⁷Rb has c₂ < 0, leading to a spin-polarized (ferromagnetic) ground state.

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The ground state (GS) for the system rotating at frequency ω is found by minimizing H rotated = H interaction + (ω₀ - ω)L [8], where L = ∑ mᵢ is the total angular momentum. For N particles in the LLL with zero center-of-mass angular momentum, the average “filling factor” of the occupied states can be defined as ν = N/Nᵥ, where Nᵥ = 2L/N is the number of vortices there would be if there were a Bose condensate (we assume here a uniform average occupation of states up to m = Nᵥ). The use of only the LLL states is physically reasonable when ω₀ - ω ≪ ω₀/Nᵥ (so that particles in the LLL with m = Nᵥ cannot lower their energy by moving to a non-LLL state with m = 0) and νc₂ ≪ ω₀, S = 0, 2 (so that perturbative corrections from mixing non-LLL states into the GS are negligible).

For the scalar case (in the LLL, without c₂), a study [9] using periodic boundary conditions found that the vortex lattice melts at a critical ν = νc ≈ 10, that incompressible fluid states occur at ν = ½, 1, ½, 2, ... < νc, and that the corresponding GS wave functions have large overlaps with the Read-Rezayi (RR) [10] series of fractional qH states. Here, for the case of vector bosons, we first propose two series of spin-singlet generalizations of the RR states [labeled SU(4)k and SO(5)k, respectively, and k = 1, 2, ...] and explain their structure. In a thermodynamic limit N → ∞ with ν fixed, they each represent incompressible liquid phases of the system, with ν = 3k/4 for the SU(4)k states and ν = k for the SO(5)k series. Then we present results for the GS’s of H rotated as a function of L, c₀, and c₂. We identify a region in the c₀-c₂ plane where the
proposed qH states with \( k = 1 \) give the exact GS’s at high values of \( L \). We demonstrate that the \( k = N/3 \) member of the SU(4) \( k \) series is an exact eigenstate and, apparently, the GS of \( H_{\text{int}} \) with \( c_2 = 0 \), \( c_0 > 0 \), at angular momentum \( L = N \). In second quantization, this state, a spin-singlet boson-triplet condensate (form the transform)

\[
| \text{BTC} \rangle = [e^{\mu_1 \delta_{\mu \nu}} b_{1 \mu_1} b_{1 \nu} b_{1 \mu_2} b_{1 \nu}]^{N/3} | 0 \rangle,
\]  

(2)

where \( b_{1 \mu} \) is a creation operator for the single-particle state \( \psi_{1 \mu} (z) \) with spin \( \mu \), where \( \mu = x, y, z \). Finally, we show the GS’s of \( H_{\text{int}} \) as a function of \( \omega \).

We now explain our analysis, starting with the construction of spin-singlet qH states for spin-1 bosons. This construction is a generalization of similar constructions for scalar and spin-1/2 particles (either of which could be electrons or bosons) [10–12]. These papers all employed a correspondence [13] between qH states and specific conformal field theories (CFT’s). This connection allows one to obtain trial qH wave functions as chiral correlators in CFT’s that are associated to a Lie algebra \( G \) and integers \( k \geq 1 \) and \( M \geq 0 \), where \( M \) is even (odd) for bosons (fermions). These states generalize the pairing familiar from the theory of superconductivity to the formation of “clusters.” The resulting qH wave functions have a property that guarantees that they are exact zero-energy eigenstates of certain model Hamiltonians. For example, starting from \( G = SU(n + 1) \) and putting \( M = 0 \), one can find completely symmetric wave functions that obey

\[
\Psi(z_1, \ldots, z_N) = 0 \quad \text{for} \quad z_1 = \cdots = z_l \quad (l \leq k),
\]

\[
\Psi(z_1, \ldots, z_N) = 0 \quad \text{for} \quad z_1 = \cdots = z_{k + 1},
\]

(3)

independent of the spins of the particles involved. Hence, these are zero-energy eigenstates of a Hamiltonian with a repulsive \( k + 1 \)-body \( \delta \)-function interaction [10] and are the unique states of the lowest \( L \) with this property. The existence of such a Hamiltonian and the fact that it has a gap in its energy spectrum ensures that a corresponding incompressible liquid phase of matter exists (when \( N \to \infty \) at fixed \( k, M \) over a range of interaction parameters, not just for the \( k + 1 \)-body model. The filling factors of these SU(n + 1) \( k \) states are

\[
\nu(n, k, M) = \frac{nk}{nkM + n + 1}.
\]

(4)

The parameter \( n \) corresponds to the number of components of an internal degree of freedom of the particles, and these models have U(n) symmetry; the clusters contain \( nk \) particles. For \( n = 1 \) this construction gives the RR states, while for \( n = 2 \) it produces spin-singlet states for spin-1/2 particles [11]. Finally, clustered qH states admit excitations (quasiparticles) of effectively fractional “charge” (i.e., particle number). The simplest of these can be viewed as the result of the adiabatic insertion of a fraction of a quantum of magnetic flux (or vorticity), where the allowed fraction is \( 1/nk \) in the present cases. States with more than three quasiparticles at well-separated fixed positions display large degeneracies, which give rise to “non-Abelian statistics” [13] and are understood for \( n = 1, 2 \) [11,14].

Our first series of clustered spin-singlet qH states of spin-1 bosons consists of the SU(4) \( k \) states (\( n = 3 \) above), where we put \( M = 0 \). The filling factor is \( \nu = 3k/4 \). The CFT construction guarantees that, for \( N \) divisible by \( 3k \), this state is a singlet under SU(3), and hence also under its SO(3) subgroup, the usual spin-rotation group. The wave function for \( N = 3kp \) particles can be written in terms of its components for particular spin states \( \mu = x, y, z \) specified for each particle (similar to [15]), as

\[
\Psi_{SU(4)}^{SU(4)} = S_{\text{groups}}[P_{\text{groups}}, Y_{222111}],
\]

(5)

where

\[
Y_{222111} (z_1^x, \ldots, z_N^x, z_1^y, \ldots, z_N^y, z_1^z, \ldots, z_N^z) = \prod_{\mu=x,y,z} \prod_{i<j} (z_i^\mu - z_j^\mu).
\]

(6)

In words, the operations \( P_{\text{groups}} \) and \( S_{\text{groups}} \) in Eq. (5) tell one to divide the \( 3pk \) bosons into \( k \) groups of \( 3p \) bosons each (\( p \) of each spin polarization), to write a factor \( Y_{222111} \) as in Eq. (6) for each group, and, finally, to symmetrize over all ways the particles can be divided over the \( k \) groups. For \( k = 1 \) there is a single group, and one finds a state of total degree \( L = 3p(2p - 1) \) that generalizes the Laughlin and Halperin states for scalar and spin-1/2 particles, respectively, and which is a zero-energy eigenstate of \( H_{\text{int}} \) for all \( c_0, c_2 \), and the unique GS when both \( g_0, g_2 \geq 0 \) since \( H_{\text{int}} \) is then positive. Putting instead \( k = N/3 \) gives \( k \) groups of three particles each, the resulting state being the \( L = N \) BTC, Eq. (2). The fundamental quasiparticles over the SU(4), qH liquids have fractional charge equal to \( \pm 1/4 \), and spin 1, for all \( k \). We note, however, that such assignments, while meaningful for \( N \gg k \), may be meaningless when \( N \sim 3k \), where the quasiparticle size is comparable to the size of the fluid drop.

An important point is that for \( c_2 = 0 \), the Hamiltonian (1) has SU(3), not just SO(3), spin-rotation symmetry. Therefore, we expect the SU(4) \( k \) states to be relevant near this line when \( c_0 > 0 \), for sufficiently large \( L \).

Our second series of qH states for spin-1 bosons is obtained from a CFT with \( G = SO(5) \) and generalizes the construction in Ref. [12]. The GS’s possess a symmetry under an SO(3) subgroup of SO(5). The general construction, which involves spin-singlet clusters of \( 2k \) particles, gives states of filling factor \( \nu = k/(kM + 1) \). Putting \( M = 0 \), we obtain qH states with \( \nu = k \). For \( k = 1 \), the wave function with values in the spin space of \( N \) spin-1 particles can be written as

\[
\Psi_{k=1}^{SO(5)} (z_i) = Pf \left[ \frac{\sigma_i \sigma_j + \tau_i \tau_j}{(z_i - z_j)} \right] \Psi_{L}^{(z_i)}.
\]

(7)

Here \( \Psi_{L}^{(z_i)} = \prod_{i<j} (z_i - z_j) \) is a spin-independent
Laughlin factor in all $N$ particle coordinates; the Pfaffian Pf is defined by $\text{Pf}(M_{ij}) = \mathcal{A}(M_{12}M_{34} \cdots M_{N-1,N})$, where $M_{ij}$ are the elements of an antisymmetric matrix and $\mathcal{A}$ denotes the operation of antisymmetrization; $\rho_i$, $\sigma_i$, $\tau_i$ are basis vectors in the spin space for particle $i$, which correspond to $x$, $y$, $z$, and the product is the tensor product. For $k = 1$, $N$ must be even, and the clustering (or pairing) of particles is seen explicitly. Clearly, there must be even (but otherwise arbitrary) numbers of particles in each of the three spin states $\rho$, $\sigma$, $\tau$. The $k = 1$ wave function for $N = 2q$ particles has total degree $L = 2q(q - 1)$. The function (7) can be viewed as spin-singlet $p$-wave pairing of composite fermions of spin 1 (for a review, see Ref. [16]). There are also excited states with unpaired charge-neutral spin-1 fermions. We note that, in the state (7), two bosons are found at the same point only if the total spin of the pair is zero, not if it is 2, and hence the state is an exact zero-energy eigenstate, of lowest $L$, for a $\delta$-function interaction that includes a projection onto spin 2. In our parametrization, that is, $c_2 = c_0/2$ or $g_0 = 0$, if and only if $c_0 > 0$, then $H_{\text{int}}$ is positive, so our $k = 1$ state is the GS at this $L$. For general $k$, the $\text{SO}(5)_k$ wave function can be written as a CFT chiral correlator and is an exact zero-energy eigenstate of a certain $k + 1$-body $\delta$-function interaction (details will appear elsewhere). In general, the quasiparticles over the $\text{SO}(5)_k$ qH state have charge $\pm 1/2$ and spin 1/2, thus displaying a fractionalization of both charge and spin.

We next report on our study (numerical and analytic) of the GS phase diagram of the model $H_{\text{int}}$. The numerical work is restricted to small values of $N$ (up to 12), but it indicates many features which we believe to hold for general values of $N$. To guide our discussion we have displayed in Fig. 1 various special directions (rays) and regions in the $c_0$-$c_2$ plane.

For $L = 0$, the GS has total spin $S = N$ for $c_2 < 0$ (ferro regime) and $S = 0$ (1) for $N$ even (respectively, odd) for $c_2 > 0$ (antiferro regime). For $c_2 = 0$, there is a single SU(3) multiplet of spin states, decomposing into unique $\text{SO}(3)$ multiplets of each spin $S = N, N - 2, \ldots$.

As $L$ increases, these two phases survive in part of the phase diagram, as compact drops of fluid, with the center of mass (CM) carrying all the angular momentum. Meanwhile, the positive $c_0$ axis gradually opens into a region that contains other phases. By the time $L$ is $\geq N$, the $c_0$-$c_2$ plane contains the three regions labeled Ia, Ib, and II in Fig. 1. The GS’s in regions Ia and Ib are similar to the GS in the “attractive” regime in the scalar case [8]. The orbital part of the GS wave function is of the form $\Psi(z_i) \propto z_i^L$, 4-body wave function inter-

![FIG. 1. Overview of $c_0$-$c_2$ plane, with special regions and directions marked.](image-url)
probably not think of the limit signature, that is, the density profile given in Fig. 2, whose multiplets listed at the steps at SU(3) multiplet. The wave functions of these GS’s at \( g \) are uniquely determined by their SU(3) and SO(5) symmetry. In Fig. 3 we display the result for \( N = 6 \) particles. The BTC is at \( L = 6 \), and the SU(4) \( L \) state at \( L = 18 \). The degenerate spin multiplets listed at the steps at \( L < 6 \) each form a single SU(3) multiplet. The wave functions of these GS’s at \( L \leq N \) are uniquely determined by their SU(3) and \( L \) quantum numbers.

The SO(5) \( L \) state found here will survive for some distance \( \omega_0 = 0 \). For \( N \) large at fixed \( \nu \), there will be several phases within region II, and, in particular, a boundary between the SO(5) \( L \) and SU(4) \( L \) phases that approaches \( \omega_0 = 0 \) as \( \omega \rightarrow \omega_0 \).

Our constructions for \( c_2 = 0 \) directly generalize to an \( n \)-component rotating Bose gas with repulsive spin-independent \( \delta \)-function interactions, implying SU(\( n \)) symmetry. In particular, we expect a “boson \( n \)-plet condensate” at \( L = (n-1)N/2 \), and SU(\( n+1 \)) \( L \) states at sufficiently small \( \nu = nk/(n+1) \).

To conclude, we have found several interesting states of matter, not containing vortices, in rotating spin-1 bosons.

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As this manuscript was being prepared, two e-prints appeared [19,20] that also address a rotating BEC. These papers point out the relevance of the SU(\( n+1 \)) \( L \) states at large \( L \) but do not discuss the other qH states or the BTC state that we consider.

6. F. Zhou, cond-mat/0108477.
18. T. Mizushima et al., cond-mat/0203242.