# EFFECTS OF ANGULAR MOMENTUM ON THE STRUCTURE OF CONDENSATES OF BOSONIC ATOMS CONFINED IN AN EXTERNAL TRAP*

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## Extended abstract

A cloud of $10^6$ neutral bosonic atoms confined by external magnetic fields to a spatial region of order $10\,\mu$m and cooled to a temperature of order 10 nK ($\sim 10^{-12}$ eV) condenses into a state in which almost all the atoms are moving in the lowest single particle quantum state of the confining potential. The study of the yrast spectrum of such a system presents a rich structure of correlation and collective modes with many analogies to issues encountered in the analysis of the effects of angular momentum on the structure of atomic nuclei.

The confining potential is quite accurately modelled as a spherical harmonic oscillator since the dimensions of the coils that produce the magnetic field are large compared with the extension of the cloud. This implies that in the absence of interactions the lowest single particle configurations exhibit an enormous degeneracy as soon as the total angular momentum $L$, is large compared with $\hbar$, since the total single particle energy is the same whether one particle is excited to a state with angular momentum $l = L$, or two particles are excited to states with $l_1$ and $l_2$ where $l_1 + l_2 = L$, or three particles excited to $l_1, l_2$, and $l_3$ where $l_1 + l_2 + l_3 = L$ *etc.* Thus the crucial issues in the discussion of the yrast spectrum is to discover the effects of the interactions between the atoms acting in this large degenerate space of states. Because of the ultra-low temperature, the de Broglie wave-length of the atoms is large compared with the range of the interatomic forces,

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and thus the two body forces are only felt through the very low energy $s$-wave scattering which gives rise to a $\delta$-function effective interaction that is proportional to the scattering length, $a$.

In order to come as quickly as possible to some interesting results I shall in this lecture confine myself to the simplest possible case: weak attractive interaction ($a < 0$). In this case the attractive interaction is optionally exploited by the configuration already encountered for $L = 0$: all atoms in the lowest state of the oscillator. This state has the smallest size and the atoms completely overlap each other with no nodes in between. Thus, the lowest quantum state with angular momentum $L$ is obtained by giving the angular momentum to the center of mass of the cloud leaving all the possibilities for relative motion unexcited. The lowest excitations with respect to this yrast state are obtained by taking $2\hbar$ of angular momentum out of the center of mass and exciting a quadrupole surface excitation of the cloud. A slightly higher excited state is obtained by taking $3\hbar$ out of the center of mass and exciting an octupole mode, *etc.* The full spectrum of these intrinsic excitations with respect to yrast can be rather simply calculated and the resulting partition function evaluated. This reveals that there is a thermal phase transition at a temperature $N/\ln L$ in units of the interaction strength; this phase transition signals the melting of the condensation of the angular momentum in the center of mass motions and is distinct from and at a much lower temperature than the London transition which signals the melting of the condensation of particles into the lowest state of the confining potential.

The yrast state with all the angular momentum carried by center of mass motion can be rather easily analyzed with further interesting results. In particular it is found that the condensate is highly "fragmented", *i.e.*, the one particle density matrix exhibits partial condensation into many different one-particle states, but, despite this fragmentation, this state retains the characteristic properties of a superfluid condensate: stability with respect to small perturbations, persistent currents, *etc.*, even in the thermodynamic limit in which the number of particles becomes arbitrarily large (while keeping the average density and angular momentum per particle constant).