Odd Parity Time-Reversal Violating Order in Cold Bosons.

"Interaction-induced chiral $p_x + ip_y$ superfluid order of bosons in an optical lattice"

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Recommended with a Commentary by Tin-Lun Ho, Ohio State University.

Bose statistics has given bosons the amazing ability to locate the single particle state with lowest energy. At sufficiently low temperatures, a macroscopic number of bosons will fall into this state, forming a condensate and magnifying the amplitude of the single particle wavefunction by a large number proportional to particle number N. For systems with time reversal symmetry, the single particle ground state has no nodes. The momentum distribution $n(\vec{k})$ of the system will then have a sharp peak at $\vec{k} = 0$, reflecting the magnification of the mean value of the ground state.

At first sight, it seems impossible for bosons to condense in an excited state, as their tendency to condense in the ground state is overwhelming. However, it was suggested some years ago that bosons might condense in the p-band of an optical lattice, provided their decay to the lowest s-band through particle collisions is prevented by energy conservation. A p-band condensate, if stable, will surely have superfluid properties unseen in the usual (s-band) condensates. At the very least, the orbital degrees of freedom of the p-state at each site, which can be viewed as a pseudo-spin, will lead to a variety of new condensates. A p-band condensate will show up as a sharp peak in $n(\vec{k})$ at the Zone edge $\vec{k} = \vec{G}$, which is the energy minimum of the p-band in a cubic lattice.

The realization of a condensate in higher band turns out to be tricky, for it is difficult to load all the particles in a higher band while leaving the lower ones empty. This problem was solved in the recent experiments of Hemmerichs group. Imagine that one starts with a Bose gas in a 2D cubic optical lattice (called A) in the lowest band as shown in fig.1. One then turns on suddenly another 2D cubi lattice (called B) whose lattice sites are at the centers of the unit cell of A as shown in fig.2. Moreover, the p-level of the B lattice is close to the s-level of A. As a result, bosons in A can tunnel to the p-levels of B, leaving the s-level of B empty. The experiment in ref.1 is performed on such a staggered 2D lattice, with a weak harmonic trap in the perpendicular direction. The system is then an array of tubes of Bose gas located at the lattice sites of the staggered lattice and the tubes are perpendicular to the 2D plane.

Theoretical studies of Bose Hubbard model in such a lattice have revealed several types of condensates, depending on hopping and interaction. These condensates are related to the symmetry of the p-orbital. In particular, one of the predicted phases is a chiral Bose condensate, formed by the hopping of bosons from the $p_x + ip_y$ state of the B lattice to the s-state of the A lattice. A summary of the phase diagram is shown in fig.3, which shows transitions between $p_{x\pm y}$ and $p_x + ip_y$ condensates. The appearance of these phases show up as two and four sharp peaks at the Zone corners in k-space in the momentum distribution $n(\vec{k})$. While the $n(\vec{k})$ measurements are consistent with theoretical prediction, there are not yet direct measurements of the $p_x + ip_y$ character, such as those in interference processes. One important property of the chiral superfluid is the presence chiral edge currents. Due to Bose condensation, the edge current will be magnified for a factor of N. The detection of this current will be a dramatic demonstration of the broken time reversal symmetry of this condensate.

In the future, there will be fermion experiments on similar kind of lattices. We shall then have excellent opportunities to study the topological properties of interacting Fermi systems in well controlled settings.

Fig.1

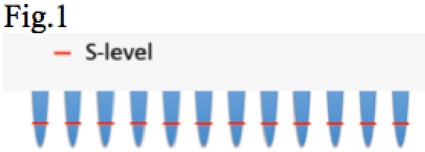


Fig.2

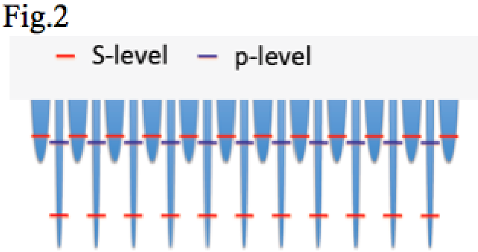
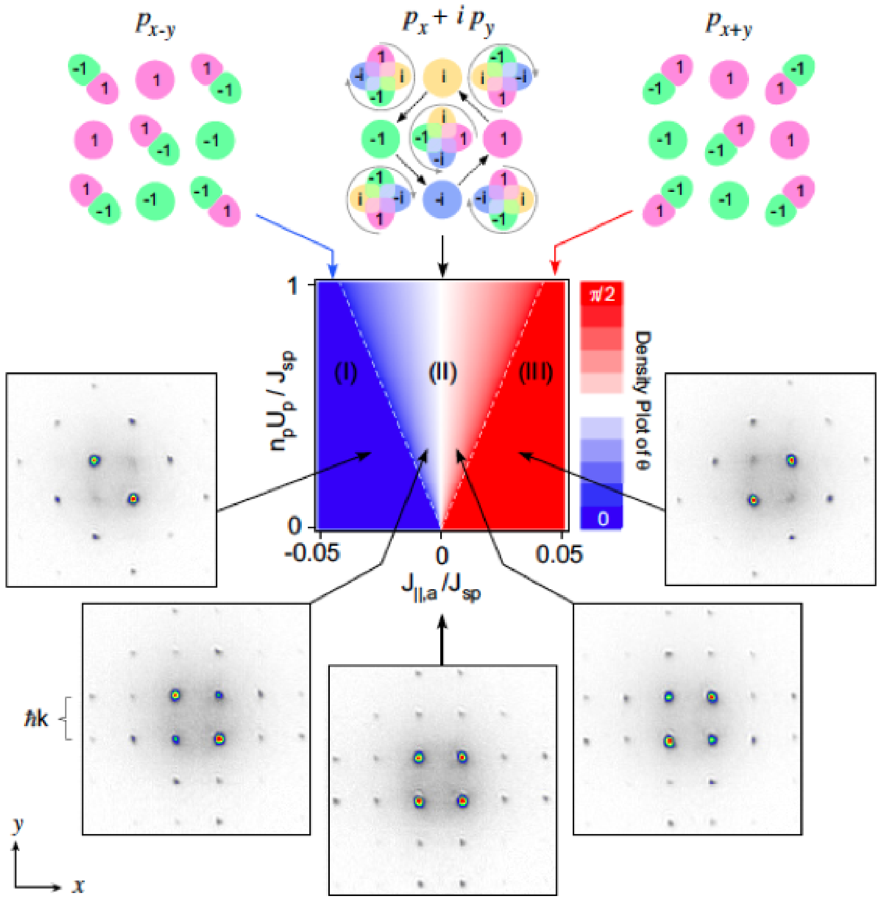


Fig.3



p_{x-y}
$p_x + i\,p_y$
p_{x+y}
1
0
-0.05
0
0.05
n_pU_p / J_{sp}
$J_{||,a} / J_{sp}$
(I)
(II)
(III)
π/2
0
Density Plot of θ
ħk
y
x