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**Press Release**

# When Bosons become Fermions

## New quantum state of matter revealed by scientists in Garching and Mainz

**There are two fundamentally distinct families of particles in nature: bosons and fermions. Being a boson or a fermion has profound consequences on the 'social behaviour' of a particle when it meets other partners. Whereas bosons tend to socialize and want to be as close to each other as possible, fermions are very independent and like to be on their own. In what represents an unprecedented manipulation of matter, researchers at the Max-Planck-Institute for Quantum Optics in Garching and the Johannes Gutenberg-University of Mainz now report in Nature (Nature, 20 May 2004) that they have been able to fermionize a gas of bosonic atoms. Under special conditions at ultracold temperatures, they have made sociable bosons act like solitary fermions. Such a gas of fermionized bosons constitutes a novel quantum state of matter called a Tonks-Girardeau gas.**

The level of sociability for atoms and subatomic particles depends on how much spin they have, which is a measure of how fast they spin around themselves. Atoms and subatomic particles with integer amounts of spin are known as bosons, and according to quantum mechanics, identical bosons prefer to occupy a single quantum state at low temperatures. Such a collective behaviour leads to striking phenomena such as Bose-Einstein condensation or the emission of Laser light. All other atoms and particles have spins equal to an integer plus an extra half. Such particles are called fermions, and quantum mechanics forbids identical fermions from occupying the same quantum state. This "exclusion principle" explains why electrons, which have spin 1/2, stack themselves into distinct energy levels in atoms and the properties of electrical conductors.

This typical fermionic or bosonic behaviour can be, however, completely altered when the interactions between the particles play a dominant role. For example, fermions have been observed to behave as bosons: when fermionic particles attract each other they can form pairs which behave as bosons. This leads to dramatic changes in their quantum behaviour and to macroscopic quantum effects such as superconductivity or the recently discovered Bose-Einstein condensation of molecules of fermionic atoms.

Now researchers at the Max-Planck-Institute for Quantum Optics and the Johannes Gutenberg-University of Mainz have demonstrated that bosonic particles can also behave as fermionic particles under special conditions. With their results the researchers have been able to realize a novel quantum state of matter which was predicted almost 40 years ago by the US physicist Marvin D. Girardeau: the Tonks-Girardeau gas. In such a gas the bosonic particles are restricted to move along one direction in space. Moreover, the particles experience a very strong mutual repulsive interaction. This repulsive interaction prevents them from being placed at the same position in space, mimicking the exclusion principle for fermions.

Under such conditions, bosons exhibit fermionic properties. For example, by measuring such properties as the energy spectrum, the density profile or the entropy of the system, one cannot distinguish the bosonic atoms from fermionic ones. Even more interestingly, the behaviour of these strongly interacting bosons is not entirely fermionic. Like fermions they tend to position themselves as far from each other as possible in space. However they are not quite as fastidious as fermions, and they do not mind sharing the same momentum state, exhibiting a characteristic momentum distribution, which neither corresponds to that of a Bose-Einstein condensate, nor to the one of an ideal gas of fermions.

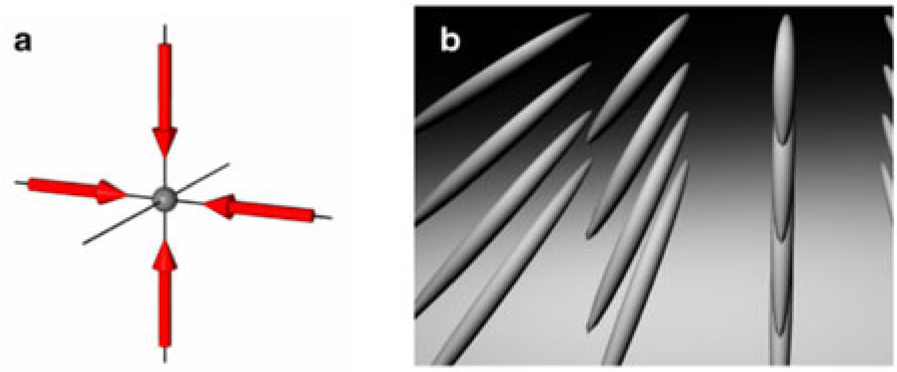

***Fig. 1:***
*By interfering laser beams at the position of the Bose-Einstein condensate a periodic array of light tubes is created. After slowly increasing the intensity of these light tubes, atoms get distributed over several thousand of them. In each of these tight tubes atoms can only move along the axial direction, their radial motion being completely frozen out.*

*Image: Max Planck Institute of Quantum Physics*

In order to realize this puzzling state of matter the researchers first had to start with an ultracold quantum gas of bosonic atoms - a Bose-Einstein condensate of rubidium atoms at temperatures of a few hundred Nano-Kelvin above absolute zero. In such Bose-Einstein condensates all the bosonic atoms occupy a single quantum state, a phenomenon that was first predicted by Albert Einstein (1879-1955) and Satyendra Nath Bose (1894-1974) in 1925 and observed experimentally for the first time in 1995. This discovery was also recently awarded with the centennial Nobel Prize in physics in 2001.

To confine the motion of the atoms to one direction, the researchers formed an array of microscopic tightly confining potential tubes. Such a confining geometry is achieved by interference of laser beams at the position of the Bose-Einstein condensate, which creates a periodic array of tubes of light (see Figure 1). After slowly increasing the intensity of these light tubes, atoms get distributed over several thousand of them. In each of these tight tubes atoms can only move along the axial direction, their radial motion being completely frozen out to zero point oscillations. This effectively realizes a one-dimensional situation for the dynamics of the atoms - they cannot move sideways but only along a single direction, quite differently to how they can move in our usual three-dimensional environment.

In order to mimic the exclusion principle for fermions the interaction between the bosonic atoms has to play a dominant role, being much stronger than the typical kinetic energy of the particles. However, atomic interactions are usually very weak and the bosonic atoms in the tubes described above could never behave as fermions. In order to fermionize the bosons the researchers have proposed and demonstrated a novel idea. The crucial point is to include a periodic potential along the direction of the tubes by using two additional interfering laser beams. The intensity of the laser light is then increased so that the dips in the laser field become very deep. In such a situation the axial motion of the atoms gets very difficult, since they have to overcome the high barriers, and they effectively behave as if the were very heavy with an extremely small kinetic energy. In this way, the researchers have effectively enhanced the role of interactions, and were able to fermionize the bosonic atoms.

To prove that they have indeed created a gas of fermionized bosons or Tonks-Girardeau gas, the researchers have made a theoretical prediction for the momentum distribution of atoms in the tightly confining tubes based on an approach in which trapped bosons acquire fermionic properties. In the experiment, the researchers then carefully measured the momentum distribution (see Figure 2), finding a remarkable agreement with the theoretical prediction.

But one does not have to stop there in this boson-fermion masquerade: Belén Paredes and Ignacio Cirac have predicted that the fermionized bosons could in fact be paired up to form bosonic type of Cooper pairs, which could again undergo Bose-Einstein condensation, yet once more underlining the fascinating physics of strongly interacting many-body quantum systems, which the researchers plan to investigate experimentally next.

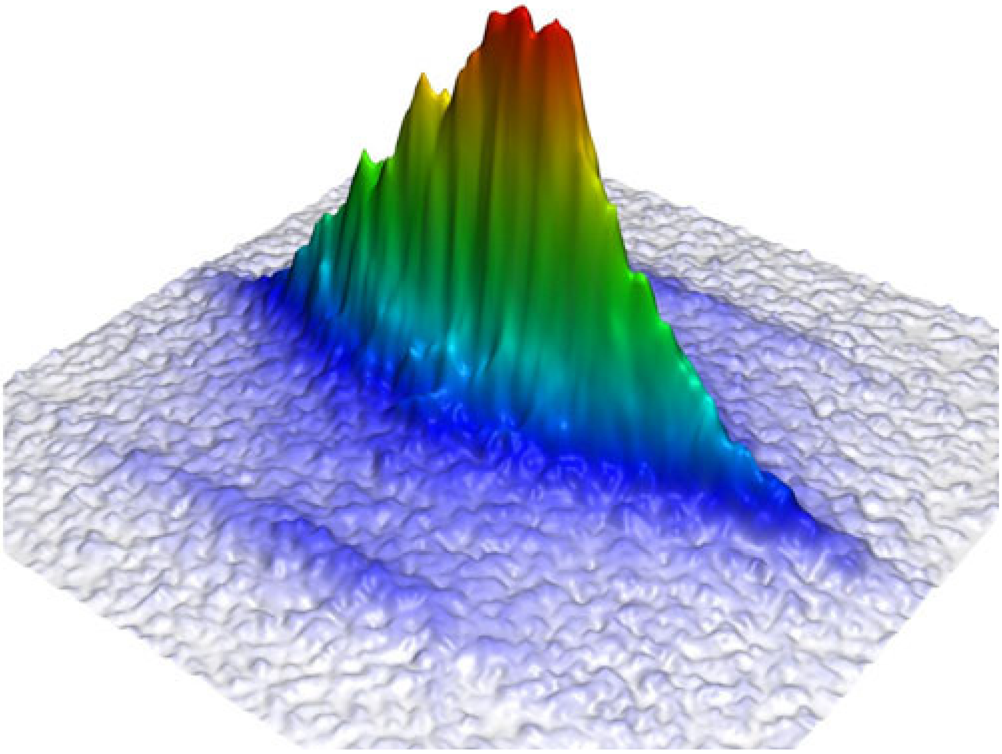

***Fig. 2:***
*Three dimensional plot of the measured momentum distribution of an array of Tonks-Girardeau gases. Such images are obtained after releasing the one-dimensional quantum gases from the array of light tubes and recording the subsequent free expansion via a photographic absorption imaging technique.*
*Image: Max Planck Institute of Quantum Physics*

**Original work:**

Belén Paredes, Artur Widera, Valentin Murg, Olaf Mandel, Simon Fölling, Ignacio Cirac, Gora V. Shlyapnikov, Theodor W. Hänsch & Immanuel Bloch
**Tonks-Girardeau gas of ultracold atoms in an optical lattice**
Nature **429**, Seite 277 (2004), 20 May 2004

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