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I Llorente-Garcia, C D J Sinclair, E A Curtis, S Eriksson, B E Sauer and E A Hinds

Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2BW, UK

E-mail: `isabel.llorente-garcia@imperial.ac.uk`

Abstract. Atom-chip technology can be used to confine atoms tightly using permanently magnetised videotape along with external magnetic fields. The one-dimensional (1D) gas regime can be realised and studied by trapping the atoms in high-aspect-ratio traps in which the radial motion of the system is confined to zero-point oscillation.

1. Introduction

Experimental developments in the miniaturisation of atom optics have opened up the possibility of realising quantum gases in one dimension using the technology of atom chips. One-dimensional systems are interesting because quantum effects are more dominant than in higher-dimensional systems, leading to striking differences in the properties of the gas due to reduced dimensionality.

Atom chips based on permanently magnetised structures are promising candidates for the creation and study of 1D gases. These chips employ small magnetic field patterns to trap atoms with the advantage of no power dissipation and the possibility of very tight atom traps. We confine ^{87}Rb atoms in long, thin traps using a permanent-magnet atom chip based on commercial videotape [1]. We have created Bose-Einstein condensates (BEC) [2] with trap aspect ratios greater than 30 using this chip. The dielectric videotape shows the added benefit of a long thermally-induced spin-relaxation time for atoms trapped near its surface.

We intend to reach the 1D regime by trapping the atoms much more tightly in the radial direction of the elongated cloud than in its axial one, so that the radial motion of the system is "frozen out". Theoretical studies predict three 1D quantum regimes depending on the temperature and number of atoms in the 1D system: a true condensate, a "quasi-condensate" and the Tonks-Girardeau gas [3]. We will discuss these regimes and how to reach them experimentally using permanent-magnet atom chips.

2. Permanent-magnet micro-traps

For our atom chip experiments we use commercial videotape whose magnetisation is produced from iron-composite needles embedded in glue and aligned parallel to each other. A recorded pattern of sinusoidal magnetisation with a period of about 100 μm creates a magnetic field that decays exponentially as the distance from the chip surface increases. Field lines are shown in figure 1(a). The addition of a uniform bias field, B_{bias}, in the x-y plane cancels the field of the

videotape at a certain height, forming a set of two-dimensional magnetic micro-traps that can be seen in figure 1(b). Atoms in weak-field seeking states are attracted towards the zero of the magnetic field at the centre of these micro-traps. Adding a small field, B_z, in the z direction removes the zero of the magnetic field in order to avoid Majorana spin flips into un-trapped states. The atoms are confined axially by the magnetic field generated by two "end wires" placed under the videotape.

$$2\pi f_r = k\, B_{bias}\sqrt{\frac{\mu_B g_F m_F}{mB_z}} \tag{1}$$

Equation (1) shows the expression for the radial frequency of oscillation of the atoms in the centre of the trap when approximating the potential by a harmonic one, which is valid for small oscillations. In this expression m is the atomic mass and $\mu_B g_F m_F$ is the usual factor in the Zeeman energy.
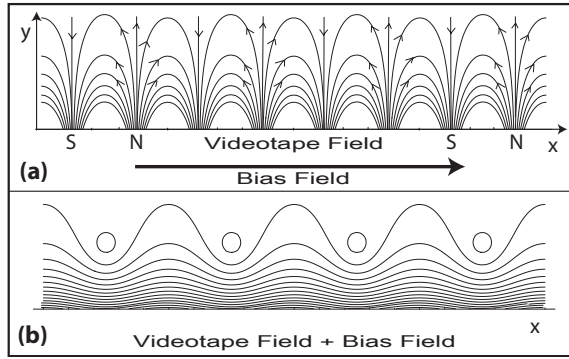

Figure 1. (a) Videotape magnetic field lines and uniform bias field. (b) Contours of constant field strength once the bias field is added. Weak-field-seeking atoms can be trapped in the circular minima.

A detailed description of the videotape atom chip and of the process of loading and trapping the atoms in the videotape traps can be found in the contribution by C. D. J. Sinclair et al. to these proceedings, as well as in reference [1].

3. Study of 1D gases with permanent-magnet atom chips

To reach the 1D regime we need to confine the atoms in a long, tube-like trap where the energy of the system is much smaller than that needed to produce radial excitations. By making the trapping potential much tighter in the radial direction than in the axial direction, and fulfilling the 1D condition ($\mu, K_B T \ll hf_r$), the radial motion is "frozen out" and confined to zero-point oscillation. Experimentally we have trapped atoms in very long, thin traps with axial frequencies between 5 and 15 Hz, and radial trap frequencies up to 20 kHz on our videotape atom chip.

Theory predicts three possible quantum regimes for 1D gases [3]: a **1D "quasi-condensate"** where density fluctuations are suppressed but phase fluctuations are still present along the length of the atom cloud; a **pure 1D condensate** where both phase and density fluctuations are suppressed; and the **Tonks-Girardeau regime**, where repulsive inter-particle interactions become so strong that the atoms cannot pass each other and the interacting bosons effectively behave like non-interacting fermions.

Arrays of tight traps formed with optical lattices have been used to study 1D gases by several groups [4]-[6]. Single traps with radial trapping frequencies less than 1 kHz have been used to
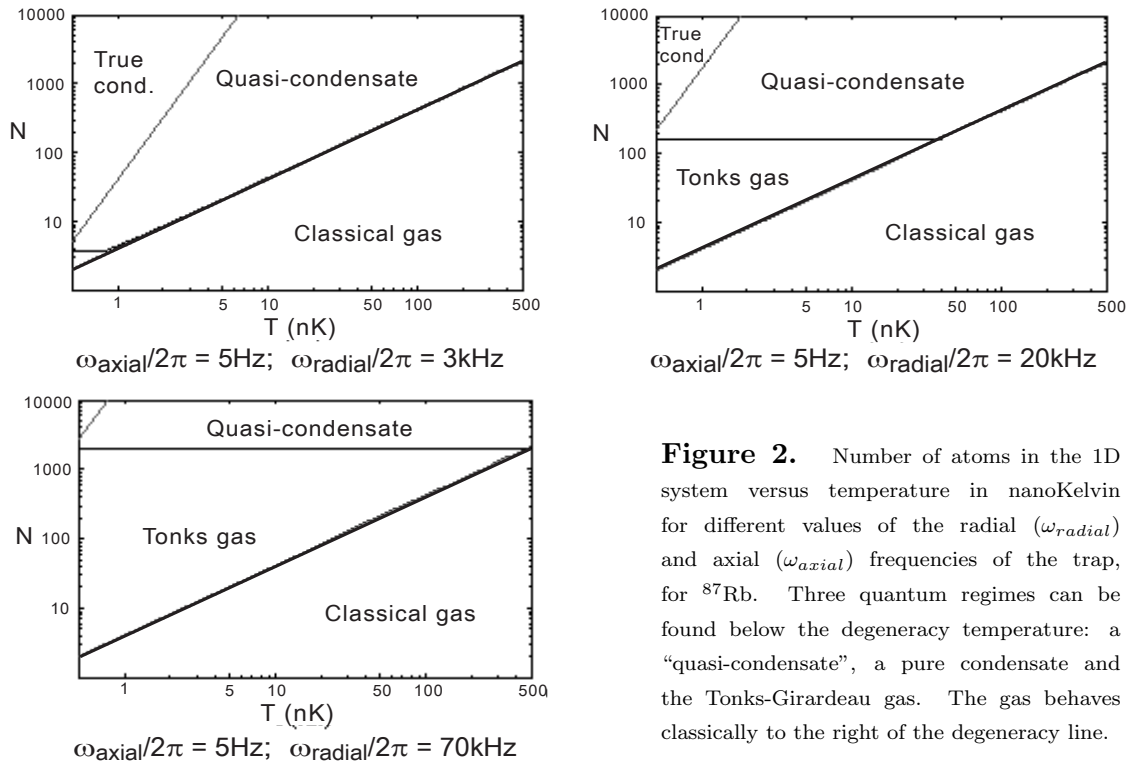
Figure 2. Number of atoms in the 1D system versus temperature in nanoKelvin for different values of the radial (ω_{radial}) and axial (ω_{axial}) frequencies of the trap, for ^{87}Rb. Three quantum regimes can be found below the degeneracy temperature: a "quasi-condensate", a pure condensate and the Tonks-Girardeau gas. The gas behaves classically to the right of the degeneracy line.

study the properties of "quasi-condensates" [7]. With our chip we plan to study the dynamics of a single trap in the 1D regime with radial frequencies greater than 1 kHz.

Figure 2 shows the different regimes of a 1D quantum gas of ^{87}Rb for three different trap frequency values accessible with our videotape chip and with other chips based on permanent magnets. An axial frequency of 5 Hz and a radial frequency of 3 kHz will enable the study of 1D "quasi-condensates" with about 2000 to 10000 atoms, at temperatures below 500 nK, at these trapping frequencies. It is difficult to reach low enough temperatures to be able to achieve a pure 1D condensate. By increasing the radial frequency up to 70 kHz the Tonks-Girardeau regime becomes accessible with as many as 2000 atoms at temperatures below 500 nK.

Theoretical studies predict important differences in the properties of the 1D gas compared to the well-studied three-dimensional (3D) case. One of these differences is the fact that in 3D there is an abrupt phase transition from incoherent thermal cloud to phase-coherent BEC, while in 1D there is a smooth transition from incoherent classical gas to pure 1D BEC, during which we encounter the 1D "quasi-condensate" regime. A quasi-condensate consists of different regions across the size of the atom cloud which are locally coherent, but the phases of these different self-coherent regions are not correlated with each other. As the temperature of the 1D system is lowered, the size of the locally coherent domains grows until the quantum 1D gas is coherent over its full size, and a pure 1D BEC is reached at such low temperatures.

Increasing the density of the system has a very different effect on the strength of inter-particle interactions in 1D compared to 3D. Perhaps counter-intuitively, inter-particle interactions in the 1D gas become stronger as the density of the system decreases. Hence, we move from the 1D weakly-interacting regime to the strongly-interacting 1D Tonks-Girardeau regime by decreasing the number of atoms. By contrast, in 3D the strongly-interacting regime requires high densities.

Another feature found in 1D gases is the reduction of rates of two-body inelastic processes

and three-body losses for weakly-interacting 1D gases, and the strong suppression of these rates for the strongly-interacting Tonks-Girardeau regime, with respect to the 3D gas rates.

Finally we also intend to measure the frequencies of the lowest collective excitation modes of the 1D gas, i.e. the dipole mode (oscillation of the centre of mass of the cloud with frequency ω_d), and the quadrupole mode (oscillation of the cloud length with frequency ω_q), the later of which theory predicts to be different from 3D. In a 3D gas the value of $(\frac{\omega_q}{\omega_d})^2$ is equal to 4 for a thermal cloud and $5/2$ for a BEC. For a 1D gas, the theoretical values of $(\frac{\omega_q}{\omega_d})^2$ are 3 for the 1D BEC and 4 for the Tonks-Girardeau regime.

4. Conclusions and future directions

It is possible to reach the 1D gas regime and study its properties using atom-chip technology. We are presently studying atom-surface effects such as spin-flip loss [2, 10] and fragmentation [1] of the cold trapped atom cloud close to the room-temperature videotape surface, in order to understand the behaviour of the system at the short atom-surface distances required to achieve high radial trap frequencies. The tight, thin traps and reduced number of atoms required for the study of 1D gases create challenges for atom detection. Integrating optical fibres and optical micro-cavities [8] onto our chip will enable us to detect low atom numbers (< 1000) in tight traps with small radii. Magneto-optical films made of thin layers of Co/Pt [9] are under investigation as possible future basis for permanent-magnet atom chips that will allow us to reach even higher trap frequencies.

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