# Exciting Collective Oscillations in a Trapped 1D Gas

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We report on the realization of a trapped one-dimensional Bose gas and its characterization by means of measuring its lowest lying collective excitations. The quantum degenerate Bose gas is prepared in a 2D optical lattice, and we find the ratio of the frequencies of the lowest compressional (breathing) mode and the dipole mode to be $(\omega_B/\omega_D)^2 \simeq 3.1$, in accordance with the Lieb-Liniger and mean-field theory. For a thermal gas we measure $(\omega_B/\omega_D)^2 \simeq 4$. By heating the quantum degenerate gas, we have studied the transition between the two regimes. For the lowest number of particles attainable in the experiment the kinetic energy of the system is similar to the interaction energy, and we enter the strongly interacting regime.

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An ultracold Bose gas in one spatial dimension is different from its two- or three-dimensional counterparts. One striking example is that Bose-Einstein condensation does not occur at finite temperature in a homogeneous one-dimensional system. In an interacting Bose gas the constraint to one dimension leads to another remarkable and counterintuitive property. With decreasing atomic density the interactions become increasingly dominant and the character of the system changes. Assuming delta-functional interactions, exact solutions have been found for the ground state and the excitation spectrum of a homogeneous one-dimensional Bose gas [1,2]. Sparked by the prospect that this unique model in many-body quantum physics could become experimentally accessible there has recently been a wave of theoretical interest in trapped 1D gases. Assuming elongated trapping geometries in which the radial atomic motion is confined to zero point oscillation, different physical regimes could be identified [3–9]. The stringent requirements for testing these models have so far not been reached in experiments.

A trapped 1D gas is characterized by a single parameter $\gamma$ which is the ratio between the interaction energy and the kinetic energy of the ground state: $\gamma = \frac{m g_{1D}}{\hbar^2 n_{1D}}$, with $m$ being the atomic mass, $g_{1D}$ the 1D coupling constant, and $n_{1D}$ the 1D density. For high densities ($\gamma \ll 1$) the system is weakly interacting, a regime which can be described by mean-field theory, and in harmonically confined 1D systems Bose-Einstein condensation is possible. When the 1D density is lowered, the kinetic energy of the ground state is reduced and may get smaller than the interaction energy, thereby transforming the gas into a strongly interacting system, where the longitudinal motion of the particles is highly correlated. For $\gamma \gtrsim 1$ the correlation length $l_c = \hbar/\sqrt{m n_{1D} g_{1D}}$ becomes shorter than the mean interparticle distance. In the limit $\gamma \to \infty$, often referred to as the Tonks-Girardeau regime, a Bose gas acquires fermionic properties due to the strong repulsive interactions. The different regimes associated with the parameter $\gamma$ are characterized by the excitation spectrum which can be probed by measuring the frequencies of collective oscillations [4,7,9]. In the two limiting cases of weak and strong interactions, the ground state properties and the excitation spectrum are explicitly known, whereas in the crossover regime many unknown issues remain to be resolved for the confined system.

The 1D regime is reached when the condition

$$\mu, k_B T \ll \hbar\omega_r \qquad (1)$$

is fulfilled, where $\omega_r$ denotes the radial trapping frequency and thus the strength of the radial harmonic confinement, $\mu$ the chemical potential, and $T$ the temperature. If the ground state extension in the radial direction $a_r = \sqrt{\hbar/m\omega_r}$ is much larger than the characteristic radius of the interatomic potential, the 1D coupling strength $g_{1D}$ can be expressed in terms of the 3D scattering length $a$ through $g_{1D} = -\frac{2\hbar^2}{m a_{1D}}$ with $a_{1D} \simeq -a_r^2/a$ being the 1D scattering length [3]. The necessity for low densities and therefore low atom numbers makes the experimental quest for 1D gases challenging. A simple estimate using the Lieb-Liniger chemical potential $\mu = 2\hbar\omega_r n_{1D} a$ shows that for a degenerate 1D quantum gas in the mean-field regime the density must obey $n_{1D} \ll 1/a$ and the number of particles must be $N \ll L/a \simeq 10^3$–$10^4$, where $L$ is the characteristic length of the system, e.g., the Thomas-Fermi radius.

There has been significant progress towards the realization of trapped 1D atomic gases over the past years. In both a $^6$Li/$^7$Li mixture [10] and $^{23}$Na [11], quantum degenerate gases have been created in very elongated traps, and features of one-dimensional condensate expansion were observed. Considering only the condensed fraction, a chemical potential of $\mu \gtrsim 0.5\hbar\omega_r$ was attained in these experiments. However, the thermal component, which was a substantial portion of the gas, was in a 3D configuration ($k_B T > \hbar\omega_r$), leaving the whole sample in an interesting crossover regime. In a similar experimental regime $^7$Li Bose-Einstein condensates with attractive

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interparticle interactions were launched into 1D matter waveguides forming bright matter wave solitons [12]. Moreover, a Bose-Einstein condensate of rubidium has been loaded into the ground state of a two-dimensional optical lattice, where the transverse oscillations have been frozen out but the tunneling rate between the tubes exceeded the axial trapping frequency, resulting in an array of strongly coupled tubes [13].

In our experiment we have realized both quantum degenerate and thermal one-dimensional atomic gases with the condition (1) being well fulfilled: for all our experiments $k_B T/\hbar\omega_r < 6 \times 10^{-3}$ and $\mu/\hbar\omega_r < 0.1$. The atoms are prepared in a 2D optical lattice which offers the advantage of an extremely tight radial confinement of only a fraction of the optical lattice wavelength. Moreover, the geometry (see Fig. 1) makes it possible to study many copies of the 1D system at the same time, thereby circumventing problems arising from the detection of very low particle numbers. The parameter $\gamma$ ranges approximately from 0.4 to 1, which is at the crossover from the mean field to the strongly correlated regime.

In the experiment, we collect up to $2 \times 10^9$ $^{87}$Rb atoms in a vapor cell magneto-optical trap. After polarization gradient cooling and optical pumping into the $|F = 2, m_F = 2\rangle$ hyperfine ground state the atoms are captured in a magnetic quadrupole trap. Subsequently, we magnetically transport the trapped atoms using a series of partially overlapping quadrupole coils [14] over a distance of 40 cm into an optical quality quartz cell, which is pumped to a pressure below $2 \times 10^{-11}$ mbar. The transfer time is 1.5 s, and we have observed transfer efficiencies larger than 80% with no detectable heating of the cloud. Finally, the linear quadrupole potential is converted into the harmonic and elongated potential of a QUIC trap (a type of magnetic trap that incorporates the quadrupole and Ioffe configuration) [15]. Radio frequency induced

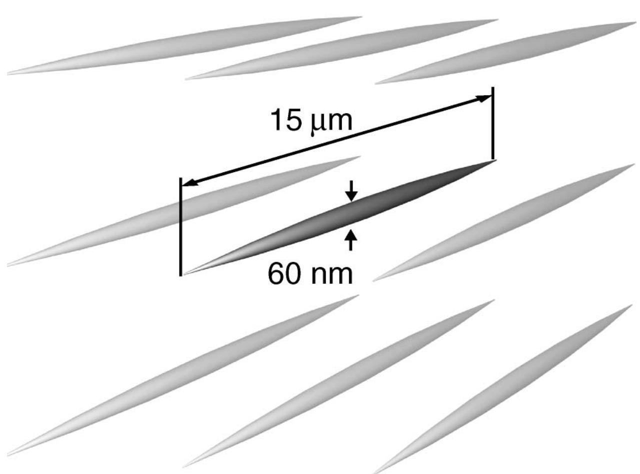


FIG. 1. The geometry and size of trapped 1D gases in a two-dimensional optical lattice. The spacing between the 1D tubes in the horizontal and vertical direction is 413 nm.

evaporation of the cloud is performed over a period of 25 s, during which the confinement is adiabatically relaxed to $\omega_\perp = 2\pi \times 120$ Hz in the radial and $\omega_\parallel = 2\pi \times 20$ Hz in the axial direction. We produce almost pure Bose-Einstein condensates of up to $3 \times 10^5$ atoms. After condensation we adiabatically change the trapping geometry to an approximately spherical symmetry with trapping frequencies of $\tilde{\omega}_x = 2\pi \times 17$ Hz, $\tilde{\omega}_y = 2\pi \times 20$ Hz, and $\tilde{\omega}_z = 2\pi \times 22$ Hz. This reduces the peak density by a factor of 4 and allows us to load the optical lattice more uniformly.

The optical lattice is formed by two retroreflected laser beams, which are derived from laser diodes at a wavelength of $\lambda = 826$ nm. At the position of the condensate, the laser beams overlap perpendicularly with orthogonal polarizations and are focused to a circular waist ($1/e^2$ radius) of 105 and 120 $\mu$m, respectively. The frequencies of the two beams are offset with respect to each other by 152 MHz. The optical potential depth $U$ is proportional to the laser intensity and is conveniently expressed in terms of the recoil energy $E_{\rm rec} = \frac{\hbar^2 k^2}{2m}$ with $k = \frac{2\pi}{\lambda}$. The two-dimensional optical lattice produces an array of tubes, tightly confined in the radial direction and spaced by the periodicity of the lattice $d = \lambda/2$ (see Fig. 1). The radial confinement of the tube is characterized by the radial trapping frequency $\hbar\omega_r \simeq 2\sqrt{s}E_{\rm rec}$, where $s = U/E_{\rm rec}$ expresses the potential depth in units of $E_{\rm rec}$. The axial confinement of the tubes is determined by the waists $w$ and intensities of the laser beams and characterized by the trapping frequency $\hbar\omega_z \simeq 2\sqrt{s}\frac{\lambda}{\pi w}E_{\rm rec}$. We have calibrated the potential depth of each of the optical lattice laser beams by measuring the frequency of small amplitude dipole oscillations along the axis of the laser beam. From the oscillation frequency we deduce the effective mass $m^*/m$ at the quasimomentum $q = 0$ in the band structure, which is a measure of the potential depth of the optical lattice [16,17]. The calibration error is estimated to be $<10\%$.

Adiabatic loading into the ground state of the optical lattice was achieved by ramping up the laser intensity to $U = 30E_{\rm rec}$ with an exponential ramp using a time constant $\tau = 75$ ms and a duration of $t_0 = 150$ ms. We have verified experimentally that all atoms are loaded into the lowest Bloch band of the optical lattice by ramping down the intensity of the lattice laser beams adiabatically and observing in the time-of-flight image, after release from the magnetic trap, that only the lowest Brillouin zone was occupied [13].

The 1D systems in the optical lattice are not perfectly isolated, but the tubes are coupled by the tunneling matrix element $J$. For sufficiently deep lattice potentials, the tunneling becomes exponentially small and contributes only a small correction of order $J/\mu$ to the 1D characteristics in the individual tubes. If $J/\mu \ll 1$ locally the gas acquires 1D properties and can be well described by a local Lieb-Liniger model, even though the whole sample is three dimensional [9]. Experimentally, we observe the disappearance of the matter wave interference pattern with increasing lattice depth when the atoms are suddenly released from the optical lattice. Higher order momentum peaks ($\pm 2\hbar k, \pm 4\hbar k, \ldots$) are usually observed at lower laser intensities [13]. We attribute this loss of coherence between the individual tubes to the very small tunnel coupling at large lattice depths, which is too small to stabilize the global phase coherence.

The different regimes of the 1D gas in the optical lattice can be determined from the excitation spectrum. The frequency ratio between the lowest compressional mode (breathing mode) and the dipole oscillation $(\omega_B/\omega_D)^2$ is a sensitive measure, both for isolated 1D systems [7] and for atoms in an optical lattice [9]. For a degenerate gas in the 1D mean-field regime, one expects $(\omega_B/\omega_D)^2 = 3$, whereas in the Tonks-Girardeau regime $(\omega_B/\omega_D)^2 = 4$. The latter frequency ratio is the same for both a thermal gas and a gas of degenerate, noninteracting fermions. In contrast, for a three-dimensional elongated condensate in the mean-field regime the ratio of the oscillation frequencies is $(\omega_B/\omega_D)^2 = 5/2$ [18–20].

We have measured the frequency of the collective excitations of the atoms in the optical lattice. The breathing mode was excited by sinusoidal intensity modulation of the optical lattice with an amplitude of $4E_{\rm rec}$ for five cycles and a frequency of 150 Hz, which is close to but not matching the expected frequency of the breathing mode. At the end of the modulation period a short (1 ms) magnetic field gradient was applied along the symmetry axis of the 1D tubes to induce a dipole oscillation of the condensate in the axial trapping potential. After a variable evolution time in the combined optical and magnetic trapping potential all confining forces were suddenly switched off [21], and we detected the atoms after ballistic expansion by absorption imaging. The density distribution of the atoms was fitted by a Gaussian to extract the position and width of the cloud. Figure 2 shows a data set of a dipole oscillation [Fig. 2(a)] and a breathing mode [Fig. 2(b)]. In order to extract the frequencies of the modes, we have fitted an exponentially decaying sine function to the position of the cloud and an exponentially decaying sine function plus a linearly increasing term to the rms axial width of the cloud. The latter accounts for the observation that there is a slight increase in the width of the cloud with longer hold times, possibly due to technical noise. The damping coefficients varied between 0 and 40 $s^{-1}$ for the dipole oscillations and between 3 and 60 $s^{-1}$ for the breathing mode. We found that the damping coefficients depend critically on the alignment of the optical lattice.

Figure 3 shows the measured ratio $(\omega_B/\omega_D)^2$ for a pure 3D Bose-Einstein condensate loaded into a 2D optical lattice for various total atom numbers. For all data points there was no discernible thermal cloud which allows us to estimate for the temperature $T/T_{c,3D} < 0.3$, where $T_{c,3D}$ denotes the critical temperature for Bose-Einstein condensation in the final magnetic trapping configuration. We compare the measured ratio $(\omega_B/\omega_D)^2$ to the theoretical prediction of [9] (solid line) and find good agreement over the wide range of atom numbers investigated. For the lowest total atom numbers $N = 1.7 \times 10^4$ the parameter $\gamma$ reaches unity in the central tube of the lattice, indicating that we are in the crossover region from the 1D mean-field regime to the Tonks-Girardeau regime. We have

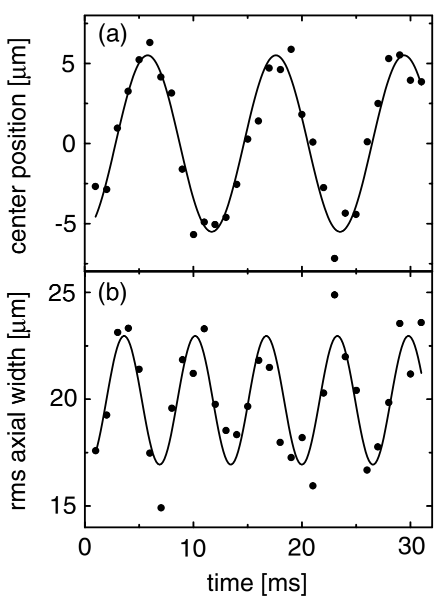


FIG. 2. Dipole oscillation (a) and breathing mode (b) of a quantum degenerate one-dimensional Bose gas. For this data set an almost pure Bose-Einstein condensate with $N = (9.8 \pm 0.8) \times 10^4$ atoms was loaded into the optical lattice and imaged after 15 ms of ballistic expansion. From the fits we obtain $\omega_D = 2\pi \times (84.6 \pm 0.4)$ Hz and $\omega_B = 2\pi \times (152.6 \pm 2.0)$ Hz.

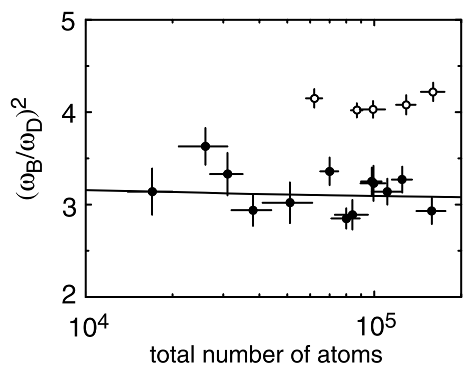


FIG. 3. The measured frequency ratio $(\omega_B/\omega_D)^2$ for a Bose condensed 1D gas (solid symbols). The solid curve is the theoretical prediction from [9] using the measured dipole frequency along the 1D tubes $\omega_z = 2\pi \times 84$ Hz and the frequency $\omega$ of the slowly varying confining potential in the transverse direction with $\sqrt{m/m^*}\omega = 2\pi \times 4$ Hz. Averaging all measurements, independent of the atom number, we obtain a frequency ratio of $(\omega_B/\omega_D)^2 = 3.15 \pm 0.22$. For a 1D gas of thermal atoms we find $(\omega_B/\omega_D)^2 = 4.10 \pm 0.08$ (open circles). The depth of the optical lattice is $30E_{\rm rec}$. The error bars reflect only the statistical uncertainties on the total atom number and fit errors on the frequencies.

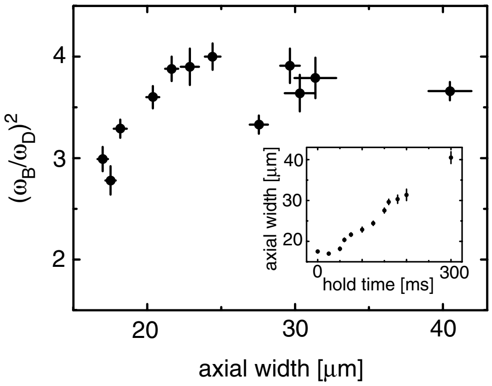


FIG. 4. The measured frequency ratio $(\omega_B/\omega_D)^2$ for a Bose gas with $7 \times 10^4$ atoms after heating in the optical lattice. The rms axial width is given after 15 ms of time of flight. The inset shows the evolution of the axial width vs hold time in the optical lattice prior to excitation of the collective modes.

estimated the number of atoms in the central tube to be 30, assuming that the overall 3D density profile is Thomas-Fermi-like and using an effective coupling constant $\tilde{g}$ which is modified by the optical lattice [17,22].

We have also loaded thermal gases into the optical lattice and obtained an average value $(\omega_B/\omega_D)^2 = 4.10 \pm 0.08$ without significant dependence on total atom number $N$ and temperature $T$ over the range of $6 \times 10^4 < N < 1.6 \times 10^5$ and $54\ \text{nK} < T < 91\ \text{nK}$. For thermal clouds we have observed that the frequency of the dipole oscillations is up to 5% smaller than for the Bose condensed clouds. We attribute this to the larger size of the thermal clouds which therefore might experience anharmonic parts of the optical potential.

To study the transition from the 1D quantum degenerate gas to the 1D thermal gas, we have prepared atomic clouds in the optical lattice with increasing noncondensed fraction but constant atom number. We have loaded an initially pure Bose-Einstein condensate of $7 \times 10^4$ atoms into an optical lattice and trapped it there for different hold times before exciting the collective modes. During the hold period, the condensate is subjected to heating by off-resonant photon scattering and possibly technical noise on the trapping fields. We find that together with the hold time the axial width of the atomic cloud increases (see inset of Fig. 4), whereas the radial size is unaffected. Since the time scale for thermalization of the 1D gas is unknown, it remains unclear whether the cloud is in thermal equilibrium, and we refrain from calculating a temperature from the rms axial width of the cloud. Figure 4 shows the measured ratio $(\omega_B/\omega_D)^2$ as a function of the rms axial width of the cloud. For increasing width the ratio $(\omega_B/\omega_D)^2$ approaches 4, which is the value for a classical noninteracting gas. From a simple estimate we deduce that the 1D gases are in a collisional regime along the axial direction, since $N_{1D}(1 - \mathcal{T}) \gg 1$, where $\mathcal{T}$ is the transmission coefficient for a 1D collision of two bosons [3] and $N_{1D} \sim 70$ is the number of atoms in a 1D tube.

In conclusion, we have realized both thermal and quantum degenerate gases in one dimension and investigated their physics by measuring the low-lying collective excitations. Our measurements show that the properties of the 1D ground state are extremely sensitive to thermal excitations and finite temperature effects must be taken into account when studying 1D gases, in particular, for the identification of the Tonks-Girardeau regime of impenetrable bosons.

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