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Thibaut Jacqmin, Julien Armijo, Tarik Berrada, Karen Kheruntsyan, Isabelle Bouchoule. In situ observation of sub-Poissonian atom-number fluctuations in a repulsive 1D Bose gas: quantum quasi-condensate and strongly interacting regimes. 2011. hal-00576883v2

HAL Id: hal-00576883

<https://hal.science/hal-00576883v2>

Preprint submitted on 17 Mar 2011 (v2), last revised 22 Jun 2011 (v4)

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***In situ* observation of sub-Poissonian atom-number fluctuations in a repulsive 1D Bose gas: quantum quasi-condensate and strongly interacting regimes**

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(Dated: March 17, 2011)

We report on local measurements of atom number fluctuations in slices of a single 1D Bose gas with repulsive interactions. For weakly interacting gases, the fluctuations are super-Poissonian at intermediate atomic densities and become sub-Poissonian at high densities once the gas enters into the quantum quasi-condensate regime. At stronger interactions, when approaching the fermionization regime, we no longer observe super-Poissonian statistics; the fluctuations go from Poissonian to sub-Poissonian as the density is increased, as those in a Fermi gas.

PACS numbers: 03.75.Hh, 67.10.Ba

Fluctuations and correlations are a very important probe of quantum many-body systems. In particular, measurements of atom number fluctuations in ultracold atomic gases have been a key tool for revealing many aspects of these fascinating quantum systems. While atom number fluctuations in a small volume of a classical ideal gas follow the Poissonian distribution, the simple account of quantum statistics modifies the correlations and fluctuations: Bose gases show atom bunching and super-Poissonian fluctuations [1, 2], whereas Fermi gases show antibunching and sub-Poissonian fluctuations [3, 4].

Many-body processes can, however, affect the fluctuations and correlations. For example, losses due to dissipative processes may lead to sub-Poissonian atom number fluctuations in Bose gases [5, 6]. More importantly, even without dissipation, the intrinsic interatomic interactions can strongly modify the fluctuations. For example, in the presence of repulsive interactions, the energetically costly atom number fluctuations are reduced and a Bose gas can show sub-Poissonian statistics. This effect has been observed in periodic lattice potentials for large ratios of the on-site interaction energy to the tunnelling energy between the sites [7, 8], with the extreme case corresponding to the Mott insulator phase where the fluctuations almost vanish [9, 10]. The same physics accounts for sub-Poissonian fluctuations in double-well experiments [11, 12]. Sub-Poissonian fluctuations of the total atom number have been also realised by controlled loading of the atoms into very shallow traps [13], in which case the atom number is determined by the balance between the interaction energy and the trap depth.

In this work, we observe for the first time sub-Poissonian atom number fluctuations in small slices of a *single* one-dimensional (1D) Bose gas with repulsive interactions, where each slice approximates a uniform system. Taking advantage of the long scale density variation due to a weak longitudinal confinement, we monitor – at a given temperature – the atom number fluctuations in each slice as a function of the local density.

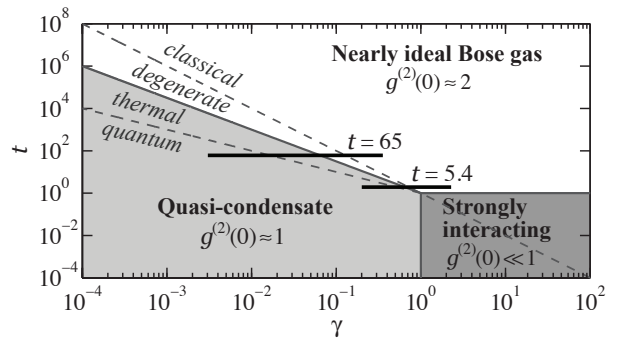


FIG. 1. Phase diagram in the γ - t parameter space of a uniform 1D Bose gases with repulsive interactions [15]. The values of the local pair correlation $g^{(2)}(0)$ are indicated for the three main regimes (white and grey areas). The two horizontal lines show the parameters explored in this paper.

For a weakly interacting gas, the measured fluctuations are super-Poissonian at low densities, and they become sub-Poissonian as the density is increased and the gas enters the quantum quasi-condensate sub-regime that is dominated by *quantum* rather than thermal fluctuations (see Fig. 1). When the strength of interactions is increased, the fluctuations are no longer super-Poissonian at low densities and remain sub-Poissonian at high densities. The absence of super-Poissonian behavior implies that the gas enters the strongly interacting regime where the repulsive interactions between bosonic atoms mimic fermionic Pauli blocking, and the quantities involving only densities are those of an ideal Fermi gas. Our results in all regimes are in good agreement with the exact Yang-Yang thermodynamic solution for the uniform 1D Bose gas with contact interactions [14].

We recall that the thermodynamics of a uniform 1D Bose gas can be characterised by the dimensionless interaction and temperature parameters, $\gamma = mg/\hbar^2 n$ and

$t = 2\hbar^2 k_B T / mg^2$ [15], where T is the temperature, n the 1D density, $g \simeq 2\hbar\omega_\perp a$ is the coupling constant, a is the s -wave scattering length, and ω_\perp is the frequency of the transverse harmonic confining potential. Figure 1 shows the different regimes of the gas, characterized by the behavior of the two-body correlation function $g^{(2)}$ and separated by smooth crossovers [15]. Of particular relevance to the present work are the quantum quasi-condensate sub-regime where $g^{(2)}(0) \lesssim 1$ [15], and the strongly interacting regime where $g^{(2)}(0) \ll 1$ [15, 16]. The two different situations studied in this work are shown in Fig. 1 by two horizontal lines at different values of t .

The experiments are performed using ^{87}Rb atoms ($a = 5.3$ nm) confined in a magnetic trap realised by current-carrying microwires on an atom chip. For the data at $t = 65$, as in Ref. [2], we use an H-shaped structure to realise a very elongated harmonic trap at ~ 100 μm away from the wires, with the longitudinal frequency $\omega_\parallel/2\pi = 5.5$ Hz and $\omega_\perp/2\pi = 3.3$ kHz. Using rf evaporation we produce clouds of ~ 3000 atoms in thermal equilibrium at $T = 16.5$ nK, corresponding to $t = 65$. We extract the longitudinal density profile from *in situ* absorption images as detailed in [17]. The local atom number fluctuations in the image pixels, whose length in the object plane is $\Delta = 4.5$ μm , are measured by repeating the same experiment hundreds of times and performing statistical analysis of the density profiles [2]. For each profile and pixel, we record the atom number fluctuation $\delta N = N - \langle N \rangle$, where $\langle N \rangle = n\Delta$ is the mean atom number. The results are binned according to $\langle N \rangle$ and for each bin we compute the variance $\langle \delta N^2 \rangle$. The contribution of optical shot noise to $\langle \delta N^2 \rangle$ is subtracted.

Figure 2 shows the measured variance $\langle \delta N^2 \rangle$ versus $\langle N \rangle$. Since $l_c \ll \max\{\Delta, d\} \ll L$ in our experiment, where $L \simeq 50$ μm is the cloud rms length, d is the imaging resolution, and l_c is the correlation length of density fluctuations [15, 18], the local density approximation is expected to correctly describe both the average density profile and the fluctuations [2, 15]. Accordingly, $\langle \delta N^2 \rangle$ is expected to follow the thermodynamic prediction [2, 17]

$$\langle \delta N^2 \rangle = \kappa k_B T \Delta (\partial n / \partial \mu)_T, \quad (1)$$

where $n(\mu, T)$ is the linear density of a homogeneous gas, and μ is the chemical potential. The reduction factor κ accounts for the finite resolution of the imaging system; it is determined from the measured correlation between adjacent pixels [17], from which we deduce the rms width of the imaging impulse response function \mathcal{A} (assumed to be Gaussian), and find that $d = 3.5$ μm and $\kappa = 0.34$.

The thermodynamic predictions for an ideal Bose gas and a quasi-condensate are shown in Fig. 2. In the quasi-condensate regime we use the equation of state $\mu = \hbar\omega_\perp (\sqrt{1 + 4na} - 1)$ [19]. The temperature is obtained by fitting the quasi-condensate prediction to the measured fluctuations at high densities. Usual features of the quasi-condensation transition are seen [2]: at low

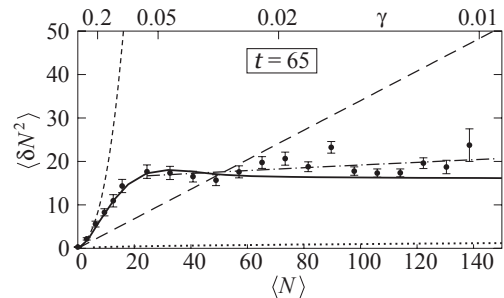


FIG. 2. Variance of the atom number fluctuations in a weakly interacting gas, for $t = 65$. The measured data are shown as circles together with statistical uncertainties. Predictions from Eq. (1) and different thermodynamic models are shown as solid (Yang-Yang), short-dashed (ideal Bose gas) and dash-dotted (quasi-condensate) lines. The long-dashed line is the Poissonian limit and the low lying dotted line is the contribution from quantum fluctuations. Here $\omega_\perp/2\pi = 3.3$ kHz, $\omega_\parallel/2\pi = 5.5$ Hz, $T = 16$ nK ($k_B T = 0.1\hbar\omega_\perp$), and $\kappa = 0.34$.

density, the gas lies within the ideal gas regime where, for degenerate gases, bosonic bunching raises the fluctuations well above the Poissonian limit; at high density the gas lies in the quasi-condensate regime where interactions level off the density fluctuations. Within the quasi-condensate regime, the fluctuations go from super-Poissonian to sub-Poissonian, with $\langle \delta N^2 \rangle / \kappa \langle N \rangle$ going from 2 to 0.44. Using the approximate 1D expression $\mu = gn$, Eq. (1) shows that the transition from super- to sub-Poissonian behavior occurs at $k_B T \simeq gn$, which is the boundary between the thermal and quantum quasi-condensate regimes [15, 18]. The fluctuations in the whole explored density domain are in good agreement with the exact 1D Yang-Yang predictions. The small discrepancy at high densities between the Yang-Yang and the quasi-condensate models is due to the transverse swelling of the cloud [2, 17]. In the following, we neglect this 3D effect and perform a purely 1D analysis.

Going beyond the thermodynamic relation (1), the variance $\langle \delta N^2 \rangle$ in a pixel is given by

$$\langle \delta N^2 \rangle = \int d^4 Z \langle \delta n(z) \delta n(z') \rangle \mathcal{A}(z - Z) \mathcal{A}(z' - Z'), \quad (2)$$

where $\int d^4 Z \equiv \int_0^\Delta dZ \int_0^\Delta dZ' \int_{-\infty}^\infty dz \int_{-\infty}^\infty dz'$, $\delta n(z) = n(z) - \langle n(z) \rangle$ is the density fluctuation, and $\int_{-\infty}^\infty dZ \mathcal{A}(Z) = 1$. Isolating the one- and two-body terms, the correlation between the density fluctuations can be written as

$$\langle \delta n(z) \delta n(z') \rangle = n \delta(z - z') + n^2 [g^{(2)}(z - z') - 1]. \quad (3)$$

The first term, when substituted into Eq. (2), accounts for Poissonian level of fluctuations, $\kappa \langle N \rangle$. Therefore, the measured *sub*-Poissonian fluctuations in Fig. 2 imply that $g^{(2)}$ takes values below 1, or $g^{(2)}(z - z') - 1 < 0$. Such anti-correlation or anti-bunching stems from quantum fluctuations. Indeed, within the Bogoliubov approximation,

valid in the quasi-condensate regime, one has [18]

$$g^{(2)}(z - z') - 1 = -\frac{1}{2\pi n} \int dk e^{ik(z-z')} (1 - f_k) + \frac{1}{2\pi n} \int dk e^{ik(z-z')} 2n_k f_k, \quad (4)$$

where $f_k = 1/\sqrt{1 + 4/(\ell_\xi k)^2}$ and $n_k = 1/(e^{\epsilon_k/k_B T} - 1)$ is the thermal occupation number of the Bogoliubov collective mode of wavenumber k and energy $\epsilon_k = \hbar^2 k^2 / (2m\sqrt{1 + 4/(\ell_\xi k)^2})$, with $\ell_\xi = \hbar/\sqrt{mg\bar{n}}$ being the healing length. The first term in the rhs of Eq. (4) which is the contribution of quantum (i.e., zero temperature) fluctuations is negative, whereas the second term which accounts for thermal fluctuations is positive [18]. Therefore, the negativity of $g^{(2)}(z - z') - 1$ implies that the quantum fluctuations give a larger contribution to $g^{(2)}(z - z') - 1$ than the thermal ones.

It should be emphasised, however, that the quantity we measure is $\langle \delta N^2 \rangle$, and as we show below, for our large values of Δ and d it is still dominated by thermal (rather than quantum) fluctuations. This is because the contribution to $\langle \delta N^2 \rangle$ of the one-body term almost cancels out the contribution of the zero-temperature two-body term, so that the remaining signal in $\langle \delta N^2 \rangle$ is actually the contribution from thermal fluctuations. Indeed, the contribution of quantum fluctuations to $\langle \delta N^2 \rangle$, calculated using Eqs. (2), (3), and (4), is

$$\langle \delta N^2 \rangle_{T=0} = \frac{\langle N \rangle}{\Delta \pi} \int_{-\infty}^{\infty} dk f_k \frac{1 - \cos(k\Delta)}{k^2} e^{-k^2 d^2}. \quad (5)$$

Since $f_k \propto k\ell_\xi$ when $k\ell_\xi \ll 1$, we find that for $\Delta \gg \ell_\xi, d$, $\langle \delta N^2 \rangle_{T=0}$ scales as $n\ell_\xi \ln(\Delta/\ell_\xi)$. On the other hand, the thermal contribution given by Eq. (1), scales as $\Delta T/g$. Therefore, the quantum contribution becomes negligible in the limit $\Delta \rightarrow \infty$, and the thermodynamic prediction of Eq. (1) is recovered [20]. For our parameters, the contribution of Eq. (5) to the total variance $\langle \delta N^2 \rangle$ is shown as a dotted line in Fig. 2.

In the weakly interacting gases, the atom number fluctuations take super-Poissonian values in the degenerate ideal gas regime. More precisely, $\langle \delta N^2 \rangle / \langle N \rangle$ takes its maximum value at the quasi-condensate transition where it scales as $t^{1/3}$ [2]. When t is decreased, the super-Poissonian zone is expected to merge towards the Poissonian limit and it vanishes when the gas enters the strongly interacting regime. This trend is exactly what we observe in Fig. 3(a), for $t = 5.4$: at large densities, we again see suppression of the atom number fluctuations below the Poissonian level but, most importantly, we no longer observe super-Poissonian fluctuations at lower densities ($\langle \delta N^2 \rangle / \kappa \langle N \rangle < 1.3$ within the experimental resolution). The fluctuations are, however, still much larger than those expected for a Fermi gas for our (not very small) value of t . Interestingly, no simple analytic theory is able to describe this crossover region, and the

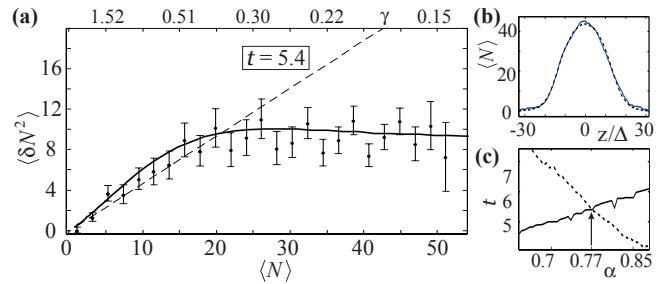


FIG. 3. (a) Variance $\langle \delta N^2 \rangle$ close to the strongly interacting regime, for $t = 5.4$. Different curves are as in Fig. 2, but for $\omega_\perp/2\pi = 18.8$ kHz, $\omega_\parallel = 7.5$ Hz, $T = 40$ nK ($k_B T = 0.044\hbar\omega_\perp$), and $\kappa = 0.47$. (b) Average density profile (solid line) together with the Yang-Yang prediction (dashes). (c) The value of t obtained from fits to the density profile (dotted line) and atom number fluctuations (solid line) for different α (see text).

only reliable theoretical prediction here is the exact Yang-Yang thermodynamic solution [solid line in Fig. 3(a)].

We now describe both the experimental techniques that allowed us to increase significantly ω_\perp in order to reach $t = 5.4$, and the calibration method used to analyse absorption images in this situation. Keeping a reasonable heat dissipation in the wires, increasing ω_\perp requires bringing the atomic cloud closer to the chip. However, using dc micro-wire currents, one would observe fragmentation of the cloud due to wire imperfections and hence longitudinal roughness of the potential [21]. To circumvent this problem, we use the modulation techniques developed in [22, 23]. The atom chip schematic is shown in Fig. 4. The transverse confinement is realized by three wires, carrying the same ac current modulated at 200 kHz, and a longitudinal homogeneous dc magnetic field of ~ 1.8 G realized by external coils. The modulation is fast enough so that the atoms experience the time-averaged potential, transversely harmonic. Monitoring dipole oscillations we measure $\omega_\perp/2\pi$ varying from 2 to 25 kHz, for ac current amplitude varying from 40 to 200 mA. The longitudinal confinement, with $\omega_z/2\pi$ varying from 5 to 12 Hz, is realised by wires perpendicular to the z -direction, carrying dc currents of a few tens of mA. After a first rf evaporation stage in a dc trap we load 6×10^4 atoms at a few μ K in the ac trap where we perform further rf evaporation at $\omega_\perp/2\pi \simeq 2$ kHz and $\omega_\parallel/2\pi \simeq 12$ Hz. Next we lower the longitudinal trapping frequency to about 7 Hz and then ramp up the transverse frequency to 18.8 kHz in 600 ms keeping the rf evaporation on during this compression. After ramping the rf power down in 100 ms and letting the cloud to thermalize for 150 ms, we switch off the wire currents and image the atomic cloud after 50 μ s with a 60 μ s long resonant probe pulse. The probe is circularly polarised and its intensity, chosen to optimise the signal to noise ratio, is about $0.2 I_{\text{sat}}$, where $I_{\text{sat}} = 1.67$ mW is the saturation intensity of the D₂ line. Finally, we get the longitudinal

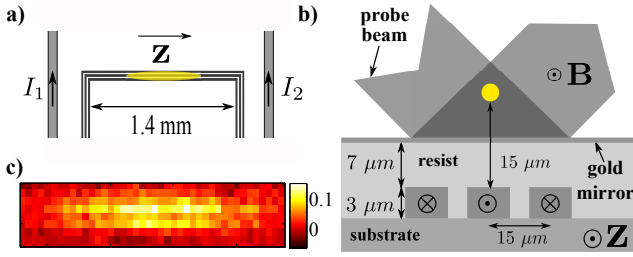


FIG. 4. (color online) (a) Wire schematic of the atom chip: three gold wires along Z carry an ac current and produce a tight transverse confining potential. The longitudinal confinement is realized with dc currents I_1 and I_2 . (b) The wires are buried under a layer of resist, which ensures electrical insulation and surface planarization. The resist is covered with 200 nm thick gold mirror that reflects the probe beam. The atoms are $15\mu\text{m}$ away from the wires and see the interference pattern produced by the probe and the reflected beam. (c) Typical optical-density image of a gas of 10^3 atoms.

profile of the cloud by summing over the transverse pixels. We typically obtain clouds at $t \simeq 1 - 6$ [24]. Taking a few hundreds of images under the same conditions, we measure $\langle \delta N^2 \rangle$ the same way as for the results of Fig. 2.

One crucial point to correctly determine the longitudinal profile is the knowledge of the absorption cross section σ . In our setup, atoms sit in an interference pattern during the imaging pulse [see Fig. 4(b)] and are subjected to a magnetic field so that the determination of σ is not simple. Following [25], we assume $\sigma = \alpha \sigma_0 / (1 + \alpha I / I_{\text{sat}})$, where I is the intensity of the probe beam, $\sigma_0 = 3\lambda^2 / 2\pi$ is the resonant cross section of the transition $|F = 2, m_F = 2\rangle \rightarrow |F' = 3, m_F' = 3\rangle$, and α is a numerical factor. Solving the optical Bloch equations (OBE) for our probe intensity and duration, we find that such a law is valid, and we obtain $\alpha = 0.75$. In this calculation, we averaged α over the distance to the chip, which is expected to be valid as atoms diffuse over a rms width of about $1\mu\text{m}$ during the imaging pulse, which is larger than the interference lattice period. The factor α can be also deduced from the mean density profile and/or the atom number fluctuations using the thermodynamic Yang-Yang predictions. Fitting both α and t to either the mean profile or the fluctuations leads to strongly correlated values of α and t but with large uncertainty in α . Combining both pieces of information, however, enables a precise determination of α . More specifically, using the Yang-Yang theory, we extract t_p and t_f from fits to the mean profile and the fluctuations, respectively, for various values of α [see Fig. 3(b) and (c)]. The intersection $t_p = t_f$ gives the correct value of α . We find $\alpha = 0.77$, in good agreement with the OBE calculation. The corresponding value of t is 5.4 and hence $T = 40$ nK.

In summary, we have realised for the first time a *single* 1D Bose gas close to the strongly interacting regime.

In contrast to realisations of arrays of multiple 1D gases in 2D optical lattices [16, 26], our experiments have allowed us to perform atom number fluctuation measurements in small slices of the gas, not possible with multiple 1D gases. In the weakly interacting regime, we have been able to reach the *quantum* quasi-condensate regime (where $k_B T < \mu = gn$) in a strictly 1D situation with $k_B T \ll \hbar \omega_\perp$. Although the two-body correlation function $g^{(2)}$ is dominated by quantum fluctuations in this regime, we have shown that the variance $\langle \delta N^2 \rangle$ is still dominated by thermal excitations. To resolve quantum fluctuations one would need to access wavelengths smaller than the phonon thermal wavelength $\hbar^2 / m k_B T l_\xi$ [20]. Our work opens up further opportunities in the study of 1D Bose gases, such as better understanding of the mechanisms of thermalisation and the role of three-body correlations.

The authors acknowledge support by the IFRAF Institute, the ANR Grant No. ANR-08-BLAN-0165-03, and the ARC Discovery Project Grant No. DP110101047.

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