Hanbury Brown and Twiss Bunching of Phonons and of the Quantum Depletion in an Interacting Bose Gas

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We report the realization of a Hanbury Brown and Twiss (HBT)-like experiment with a gas of interacting bosons at low temperatures. The low-temperature regime is reached in a three-dimensional optical lattice and atom-atom correlations are extracted from the detection of individual metastable helium atoms after a long free fall. We observe, in the noncondensed fraction of the gas, a HBT bunching whose properties strongly deviate from the HBT signals expected for noninteracting bosons. In addition, we show that the measured correlations reflect the peculiar quantum statistics of atoms belonging to the quantum depletion and of the Bogoliubov phonons, i.e., of collective excitations of the many-body quantum state. Our results demonstrate that atom-atom correlations provide information about the quantum state of interacting particles, extending the interest of HBT-like experiments beyond the case of noninteracting particles.

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In systems of noninteracting and indistinguishable quantum particles, correlations are rooted in quantum statistics. A paradigmatic example is the bunching of photons received from a source, as described by Glauber's quantum formalism [1] to interpret the Hanbury Brown and Twiss (HBT) observation of intensity [2] or photon [3] correlations. Such a method yields information both on the photon statistics (chaotic vs fully coherent [4]) and on the spatial distribution of the emitters, i.e., on the size of the source [5].

This approach pioneered by Hanbury Brown and Twiss was successfully extended to characterize quantum states in various situations, ranging from high-energy physics [6] and solid-state devices [7,8] to cold atoms [9–16]. In noninteracting atomic gases at thermal equilibrium, the bunching (for bosons) [10–13] and antibunching (for fermions) [14–16] is set by the quantum statistics and the thermal occupation of single-particle states. On the other hand, atom-atom correlations are absent in a fully coherent Bose-Einstein condensate (BEC) [11,12], in analogy with the lack of photon-photon correlations in a single mode laser beam [4].

In contrast, HBT-like measurements with interacting particles are scarce. In optics, the role of nonlinearities during the propagation from the source to the detector was studied [17], but interacting photon fluids as a source [18] have not yet been probed. With atoms, two-body correlations were used to characterize the coherence properties of weakly interacting Bose gases across the Bose-Einstein transition [19], in a regime where the temperature exceeds the interaction energy. In the opposite regime where interactions dominate, one may observe the interplay between quantum statistics and interactions in many-body systems. This is the goal of the experiment presented here.

In this Letter, we report on the measurement of momentum-momentum correlations in an ensemble of interacting atoms, in the low-temperature regime dominated by interactions. This regime is achieved by using a three-dimensional (3D) optical lattice to enhance the interactions. The two-body correlations are extracted from detecting individual metastable helium atoms ($^4He^*$) after a long free fall [20,21]. We characterize the bunching properties—amplitude and width of the HBT bump—and highlight the differences from previous findings in noninteracting ensembles. These remarkable differences are interpreted in the framework of the Bogoliubov theory and are attributed to the statistical properties of the quantum depletion and of the collective excitations—Bogoliubov phonons—in the ensemble of interacting atoms. Surprisingly, the agreement with the Bogoliubov theory extends well beyond the temperature range where this theory is anticipated to be valid. Investigating this experimental observation is an interesting direction for future theoretical works using more sophisticated approaches.

In analogy with HBT experiments with an incoherent source of light, where photon correlations are measured in far-field, HBT experiments with thermal He^* gases [11,13,15] look for atom correlations after a long free fall, i.e., in the basis of single-particle momentum states $|\mathbf{k}\rangle$. For each sample released onto a position- and time-resolved detector sensitive to individual He* atoms, the atom distribution is recorded in 3D, and the two-body correlation function for that sample is calculated over a volume of interest $\Omega_{\mathbf{k}}$. Repeating the procedure with many samples, one averages to obtain an experimental evaluation of the volume integrated two-body correlation function [22]

$$g^{(2)}_{\Omega_{\mathbf{k}}}(\delta\mathbf{k}) = \frac{\int_{\Omega_{\mathbf{k}}} \langle a^\dagger(\mathbf{k}) a^\dagger(\mathbf{k}+\delta\mathbf{k}) a(\mathbf{k}) a(\mathbf{k}+\delta\mathbf{k})\rangle d\mathbf{k}}{\int_{\Omega_{\mathbf{k}}} \langle n(\mathbf{k})\rangle \langle n(\mathbf{k}+\delta\mathbf{k})\rangle d\mathbf{k}}, \quad (1)$$

where $a^\dagger(\mathbf{k})$ [respectively $a(\mathbf{k})$] is the creation (respectively annihilation) operator associated with momentum $\mathbf{k}$.

In an ideal (noninteracting) and noncondensed Bose gas at thermal equilibrium, one expects $g^{(2)}(0) = 2$ because of (chaotic) Gaussian statistics. The Gaussian nature of the statistics derives from the random and uncorrelated populations of the momentum states at thermal equilibrium [23,24]. Moreover, the in-trap density of a noncondensed Bose gas has a Gaussian shape with a rms size $s_{\mathrm{th}} = \sqrt{k_B T/m\omega^2}$, and the bunching bump has therefore a Gaussian shape with a width (half-width at $1/e$) $\sigma_k^{\mathrm{ideal}} = 1/s_{\mathrm{th}}$ [11,23]. This relation is analogous to that used to deduce the angular size of a star from the intensity HBT correlation length [5]. This description of atom correlations also applies to weakly interacting bosons when the temperature largely exceeds the interaction energy [11,13].

In the opposite low-temperature regime where interactions dominate, the bunching properties differ because interactions affect the population statistics of the $|\mathbf{k}\rangle$ states. To get some insight into this complex physics, we use the Bogoliubov approximation for interacting bosons [25]. The interacting Bose gas is described as a many-body ground state—the condensate and the quantum depletion—and an ensemble of noninteracting (quasiparticle) excitations. Even though both the quantum depletion and the Bogoliubov excitations contribute to the noncondensed fraction, they have a very different nature. The quantum depletion, present at $T = 0$, corresponds to a pure entangled state of atomic pair with opposite momenta. The Bogoliubov excitations, only present at $T > 0$ consists of a thermal state of noninteracting (quasiparticles) bosons with populations set by the temperature and a Gaussian statistics. Because the Bogoliubov transform between particle and quasiparticle operators is linear, the statistics of the particle momenta associated with those quasiparticles is Gaussian as well, hence $g^{(2)}(\delta\mathbf{k} = \mathbf{0}) = 2$ [26–28]. Quite remarkably, a bunching at $\delta\mathbf{k} = \mathbf{0}$ is also expected for atoms belonging to the quantum depletion. That bunching stems from the fact that when one observes atoms with momenta almost equal, the correlations are measured between atoms belonging to two different pairs. The density matrix describing these atoms, obtained by tracing over the second partners of each pair, which are ignored, has a chaotic character. This origin is analog to that of the thermal (chaotic) statistics encountered when one observes only one partner of parametric-down conversion photon pairs [29] or of atom pairs produced in a two-body collision process [30,31].

For an interacting gas described within the Bogoliubov approximation, the width σ_k^B of the two-body correlation bump in $\mathbf{k}$ space is expected to behave differently from the $1/\sqrt{T}$ variation of an ideal thermal gas [26]. At $T = 0$, the only states relevant to the bunching belong to the quantum depletion. Their spatial in-trap extent, which is limited to the BEC radius R_{BEC}, determines $\sigma_k^B(T = 0)$. Since the BEC rms size is $\sim R_{\mathrm{BEC}}/\sqrt{2}$, a rough estimate is $\sigma_k^B(T = 0) \sim \sqrt{2}/R_{\mathrm{BEC}}$, in analogy with $\sigma_k^{\mathrm{ideal}} = 1/s_{\mathrm{th}}$. At small nonzero temperatures ($k_B T \ll \mu$), low-lying Bogoliubov excitations are populated, whose spatial in-trap size hardly extends beyond R_{BEC} as well. When the temperature increases, the Bogoliubov excitations progressively extend out of the condensate and $\sigma_k^B(T)$ should slowly decrease with increasing T. In the low-temperature regime, both quantum depletion and thermal Bogoliubov excitations are thus expected to significantly contribute to the bunching, leading to a width is definitely smaller than that of an ideal thermal gas.

At sufficiently low temperatures, the above description for harmonically trapped interacting bosons also applies when a 3D shallow optical lattice is present. In shallow lattices, the ratio U/J of the on-site interaction energy U to the tunneling amplitude J [see Fig. 1(a)] is smaller than that of the Mott transition, and the gas is Bose-condensed at low temperatures. At small momenta, the usual Bogoliubov description still holds provided one uses the effective mass $m^* = \hbar^2/2Jd^2$ (d is the lattice spacing, corresponding to a momentum $k_d = 2\pi/d$) and trap frequency $\omega^* = \omega\sqrt{m/m^*}$ [32]. This description is accurate in the low-temperature regime ($T < U$) investigated in this work where the physics is dominated by excitations in the lower, linear part of the dispersion relation and have a collective nature. Moreover, the bunching properties of ideal lattice bosons are identical to those of ideal bosons in the same harmonic trap, since $m^*\omega^{*2} = m\omega^2$. Using an optical lattice thus appears specially promising to reveal the effect of interactions, with the additional advantage of reinforcing the strength of interactions and facilitating the desired $k_B T \ll \mu$ regime.

The experiment starts with the production of a ^{4}He* BEC with $N = 40(4) \times 10^3$ atoms which is loaded in a 3D optical lattice of amplitude $V = 9.5E_R$ [20], with $E_R/h = h/8md^2 = 20.7$ kHz and $d = 775$ nm. The overall harmonic trap is isotropic, with a frequency $\omega/2\pi = 300(20)$ Hz. With the lattice amplitude we use, we have $U/J \simeq 10$ ($U/h = 4350$ Hz and $J/h = 450$ Hz). The interaction energy is $\mu = n_0 U$, where the lattice filling n_0 at the trap center is close to one in this work ($0.9 \leq n_0 \leq 1.6$). The critical temperature for Bose-Einstein condensation is $T_{\mathrm{BEC}} = 5.9(2)J/k_B$ [20].

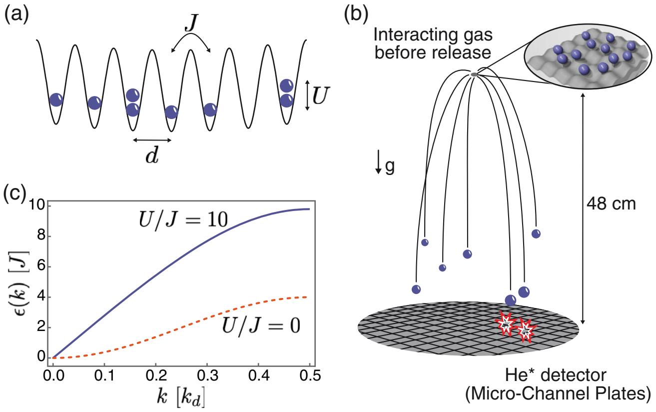

FIG. 1. (a) Interacting metastable helium $^4He^*$ atoms are loaded into a 3D optical lattice of spacing $d = 775$ nm. The tunneling energy is denoted J and the on-site interaction energy U. In this work, we set $U/J = 10$. (b) Sketch of the detection method. Atoms are released from the lattice and reach the He* detector after a long free fall (325 ms) that maps the momentum distribution of the trapped atoms into the measured spatial distribution. The use of a microchannel plate, in combination with delay-line anodes (not shown), allows for the detection of individual atoms in three dimensions [20] from which the HBT correlations are extracted. (c) Dispersion relation of the Bogoliubov excitations of the interacting gas in the lattice (solid blue line, $U/J = 10$) and of noninteracting particles in the lattice (dashed orange line, $U/J = 0$). The collective nature of the excitations is dominant in the linear part of the Bogoliubov spectrum at low energies, which is associated with phonons.

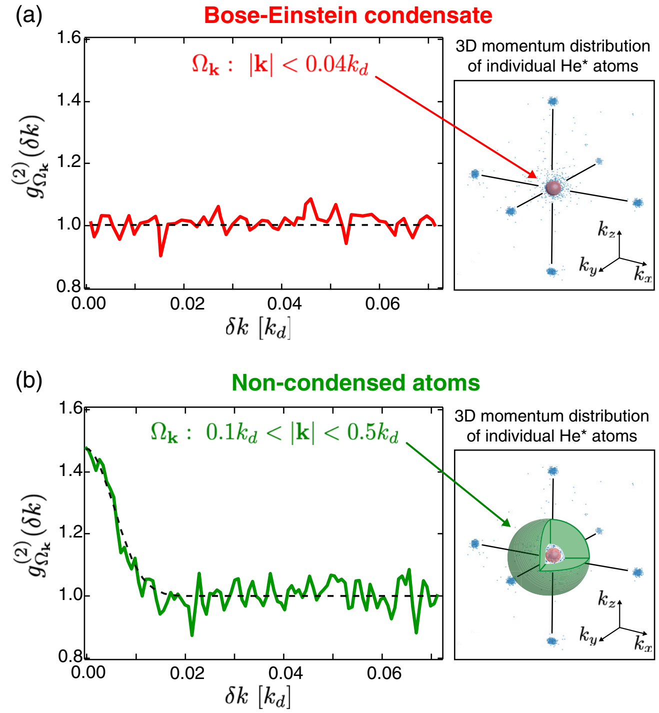

FIG. 2. Two-body HBT correlations in a strongly interacting lattice Bose gas at $T = 2.9J$. The plots are 1D cuts through the 3D correlation function along the lattice axis $\mathbf{u}_x$ with $\Delta k_\perp = 10^{-2} k_d$. (a) Two-body correlation function $g^{(2)}_{\Omega_\mathbf{k}}(\delta k)$ in the condensate. Inset: the red sphere depicts the volume $\Omega_\mathbf{k}$ ($|\mathbf{k}| < 0.04 k_d$) over which the correlations are calculated. We find $g^{(2)}_{\Omega_\mathbf{k}}(\delta k_x) = 1.0(1)$ for the condensate mode, i.e., no bunching as expected when one mode only is populated. (b) Two-body correlation function $g^{(2)}_{\Omega_\mathbf{k}}(\delta k)$ in the noncondensed fraction. Inset: the green region depicts the volume $\Omega_\mathbf{k}$ ($0.1 k_d < |\mathbf{k}| < 0.5 k_d$) over which the correlations are calculated. Note that the peaks associated with the condensate are excluded from this volume. One observes a well contrasted bunching whose bell shape is fitted with a Gaussian function (dashed line) to quantify the bunching properties.

We measure 3D single-atom-resolved distributions with the He* detector after a free fall of ~325 ms [see Fig. 1(b)] [20]. Since interactions do not affect the expansion from a lattice with less than two atoms per site [20,21], the long free fall maps the in-trap momentum distribution on the measured spatial distribution. Recording the 3D momentum distributions provides a natural separation of the condensate from its depletion. Indeed, the $\mathbf{k}$-space density of a lattice BEC is made of periodically spaced (period k_d) sharp peaks of width $\sim 1/R_{\mathrm{BEC}}$, while the noncondensed fraction—quantum depletion and thermal phonons—extends over the entire Brillouin zone of width k_d. Because $R_{\mathrm{BEC}} \simeq 23d \gg d$ here, the contribution of the noncondensed fraction is negligible in the $\mathbf{k}$-space volume $\sim R_{\mathrm{BEC}}^{-3}$ occupied by the condensate. We exploit this property to perform the integral of Eq. (1) over different volumes $\Omega_\mathbf{k}$, which allows us to investigate the HBT correlations in the two components separately (see Fig. 2). We determine the correlation properties along one lattice axis at a time, with a small transverse integration of $\pm \Delta k_\perp \leq 1/R_{\mathrm{BEC}}$ to increase the signal-to-noise ratio [33].

An example of measured correlation functions $g^{(2)}_{\Omega_\mathbf{k}}(\delta k)$ in the two components is plotted in Fig. 2. We find that $g^{(2)}_{\Omega_\mathbf{k}}(\delta k)$ is constant and equal to 1 in the condensate [see Fig. 2(a)], i.e., no bunching is observed. This is consistent with the fully coherent nature of the condensate [23]. In contrast, a well-contrasted bunching is visible in the noncondensed fraction [see Fig. 2(b)]. In the following, we analyze and discuss the bunching properties of the noncondensed fraction.

To exploit our data, we fit the bell-shaped 1D cuts $g^{(2)}_{\Omega_\mathbf{k}}(\delta k_j)$ ($j = \{x, y, z\}$) of the bunching bump along the reciprocal lattice axes with Gaussian functions. We find that $g^{(2)}_{\Omega_\mathbf{k}}$ is isotropic, a property consistent with the isotropy of the trap geometry. In the analysis of the bunching bump, we account for the transverse integration $\Delta k_\perp$ and the resolution of the He* detector [rms width $\sigma = 2.8(3) \times 10^{-3} k_d$] to extract the bunching amplitude $g^{(2)}(0) - 1$ and width σ_k [33]. Note that the data shown in Fig. 2(b) are the raw data before the deconvolution with the point spread

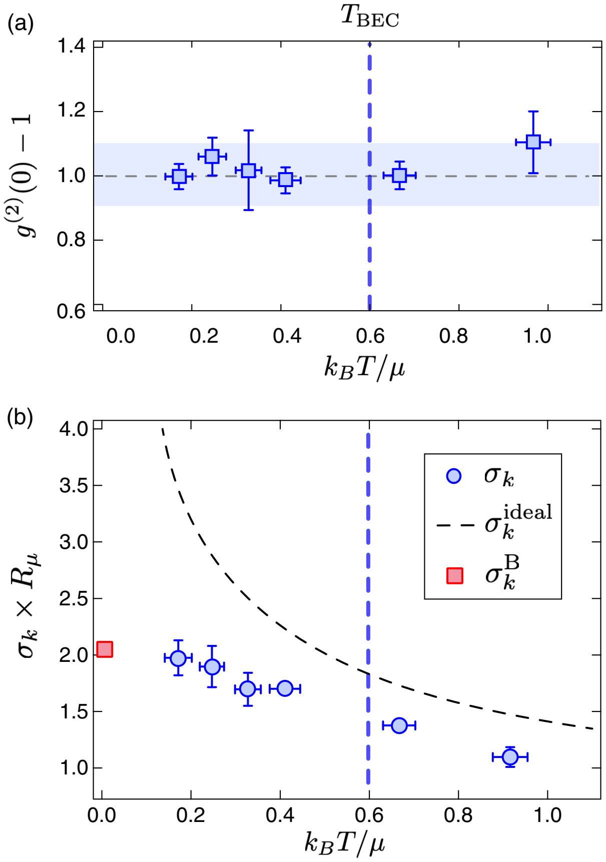

FIG. 3. (a) Bunching amplitude $g^{(2)}(0)-1$ in the noncondensed fraction as a function of the reduced temperature k_BT/μ. The measurements are consistent with $g^{(2)}(0)=2$, i.e., with a chaotic statistics at any temperature. The vertical blue dashed line in both panels signals $T_{\rm BEC}$. (b) Two-body correlation width σ_k plotted as a function of k_BT/μ. For each temperature, the value of the temperature-dependent interaction energy $\mu(T)=n_0(T)U$ in the experiment is calculated from the lattice filling n_0 at the trap center. σ_k is expressed in units of $(R_\mu)^{-1}=\sqrt{m\omega^2/2\mu(T)}$. R_μ coincides with the BEC radius at $T=0$, $R_\mu(T=0)=R_{\rm BEC}$. The red square corresponds to a numerical calculation of the correlation width σ_k^B for a harmonically trapped *one-dimensional* interacting Bose gas in the Bogoliubov approximation, with parameters consistent with the *three-dimensional* experiment (see main text and [33]). The dashed black line is the prediction $\sigma_k^{\rm ideal}=\sqrt{\hbar\omega/k_BT}$ for noninteracting bosons at thermal equilibrium, for which $\sigma_k^{\rm ideal}R_\mu=\sqrt{2\mu/k_BT}$.

function of the detector, i.e., the amplitude of the bump in Fig. 2(b) is smaller than the bunching amplitude $g^{(2)}(0)-1$ shown in Fig. 3(a) because of the resolution of the detector. Based on this protocol, we investigate the bunching properties across the BEC transition, while keeping the ratio $U/J=10$. The temperature T is varied by heating the gas in a reproducible manner [20] and calibrated by comparison with *ab initio* quantum Monte Carlo calculations [33]. The results are plotted in Fig. 3.

First, we find that the bunching amplitude is constant with temperature and equal to $g^{(2)}(0)-1=1.0(1)$ [see Fig. 3(a)]. At large temperatures $T>T_{\rm BEC}$, this observation corresponds to the usual HBT bunching of thermal bosons. This result extends below $T_{\rm BEC}$ and it can be interpreted in terms of the Bogoliubov picture of noninteracting quasiparticles given in the introduction, even though the relatively large noncondensed fraction might suggest that interactions between quasiparticles should be important. This quite surprising observation can be related to the fact that, in homogenous systems without a lattice [34,35], the Bogoliubov approach was shown to be reliable up to values of the quantum depletion (~15%) similar to that of our experiment. Measuring $g^{(2)}(0)\simeq 2$ for $k_BT/\mu\leq 0.4$ thus confirms the chaotic statistics of the thermally excited Bogoliubov phonons. Moreover, this result extends to temperatures as low as $k_BT/\mu=0.17$ where an equal fraction of atoms belong to the quantum depletion and to the Bogoliubov phonons. This suggests that $g^{(2)}(0)=2$ also for the quantum depletion, albeit for the different mechanism sketched in the introduction, i.e., a partial trace over the atom pairs in the quantum depletion.

Second, the bunching width σ_k is systematically smaller than that of ideal bosons $\sigma_k^{\rm ideal}$, in the same trap at the same temperature [see Fig. 3(b)]. This difference is more pronounced at small values of k_BT/μ as a result of interactions. For $T>T_{\rm BEC}$, one expects to observe the width corresponding to a thermal gas with interactions that broaden the in-trap size with respect to that of an ideal thermal gas. This prediction is compatible with our observation of σ_k below $\sigma_k^{\rm ideal}$. Note that we could not increase the temperature beyond $k_BT\sim 0.9\mu$ while keeping the atoms in the lowest lattice band. In the opposite low-temperature regime, the value $\sigma_k\simeq 2/R_\mu$ corresponds to an in-trap size close to that of the condensate $R_{\rm BEC}=R_\mu(T=0)$. In an attempt to be quantitative, we have numerically solved the simplified case of a trapped 1D interacting Bose gas in the Bogoliubov approximation with parameters consistent with our 3D experiment. More specifically, we use in the numerics the ratio $\mu/\hbar\omega=51$ identical to that of the experiment $\mu/\hbar\omega^*=\langle n_0\rangle U/\hbar\omega^*$, and the 1D integral of Eq. (1) is calculated for the noncondensed atoms only (excluding the region $kR_{\rm BEC}<10$) using a 3D-like weight $\propto k^2$ [33]. The numerical result σ_k^B (red square) is compatible with our measured low-temperature σ_k. Since the value of σ_k^B crucially depends on the collective nature of the excitations and can be unambiguously attributed to the spatial extension of the Bogoliubov phonons and quantum depleted atoms within the condensate [33], we ascribe the measured width to the same physical origin. A theoretical model quantitatively accurate at any temperature would require more sophisticated techniques that go beyond the free-space linearized Bogoliubov approximation used here, so to explicitly include the Bragg folding of the Bogoliubov dispersion in the lattice and the interactions between quasiparticles due to the relatively large interaction strength and high temperature. This will be the subject of future studies.

In conclusion, we have observed and fully characterized the atom bunching occurring in the noncondensed fraction of an interacting Bose gas. We have shown that the observed characteristics of that bunching reflect the interplay of interactions and quantum statistics, through the properties of phonons and of the quantum depletion. Our results thus demonstrate that momentum-momentum correlations provide information about the quantum state of strongly interacting bosons, extending the interest of HBT-like experiments beyond the case of non-interacting particles. This method will be used to look for two-body correlations at opposite momenta that are expected for the quantum depletion and other many-body phenomena [36]. Such a measurement will demand to achieve the large signal-to-noise ratio required at finite temperature [28], but will be of great importance to directly reveal pairing mechanisms.

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