Observation of Quantum Depletion in the Momentum Distribution from a Magnetically Trapped Bose-Einstein Condensate

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The recent observation of quantum depletion in a Bose-condensed gas of helium atoms released from an optical dipole trap is puzzling, as current theoretical understanding is that the depletion should not be observable after trap switch off in the presence of interactions. To shed some light on this problem, we attempt to replicate the results published in [1]. We observe quantum depletion of a Bose-Einstein condensate released from a magnetic trap, evident as a long tail at large momenta with the density scaling as k^{-4}. The values of the Tan contact constant we measure are slightly larger than those predicted by local density theory, although the discrepancy is smaller than for the results reported in [1]. Our observation suggests that the results seen here and in [1] are not an experimental anomaly, but rather demand new theoretical investigation to determine why the tails are visible.

INTRODUCTION

Quantum depletion is an interesting many-body phenomenon where not all atoms in a Bose-Einstein Condensate (BEC) are in the ground state, even at absolute zero. Repulsive interactions between atoms in the condensate cause number of single-particle states above the ground state become occupied. A recent experiment [1] was able to see signs of quantum depletion in the large k tails of an interacting BEC released from an optical dipole trap, using the high-resolution and large dynamic range of detection offered by metastable helium (He*) [2]. A separate experiment on a strongly interacting BEC in a uniform potential probed with Bragg scattering showed that the depletion could be tuned with the interaction strength [3].

In current theory however, the quantum depletion seen in [1] is not expected to be observed, as the trap switch off suggests that the k^{-4} tails should adiabatically vanish during the expansion after trap switch off [4]. This observation was supported by an experimental result that failed to observe the tails [5]. To help resolve this discrepancy, we reproduce the experimental procedure in [1] as faithfully as possible but with a magnetically trapped BEC.

METHODS

We start with a BEC of $\sim 10^6$ He* atoms in the $m_F = +1$ sub-level of the 2^3S_1 state in a bi-planar quadrupole magnetic trap [6], with trapping frequencies $(\omega_x, \omega_y, \omega_z)$ of $\sim 2\pi \times (50, 500, 500)$ Hz. To generate BECs with different temperatures/thermal fractions, we vary the endpoint of the Radio Frequency (RF) ramp used in the evaporation stage that produces the ultracold atoms.

After preparation, the magnetic trap is then switched off rapidly in $\sim 100\mu$s. 2 ms after trap switch-off, RF radiation is applied for 1 ms to transfer 42(3)% of atoms to the magnetically insensitive $m_F = 0$ sub-level. To ensure a uniform transfer efficiency for all k, the RF waveform is a linear ramp in frequency centred around 1.645 MHz ($\approx$ the Zeeman splitting between $m_F = 0, 1$ sub-levels) with a span of ± 0.5 MHz. The RF sweep to spin flip the atoms is necessary to avoid detector saturation and distortion due to background magnetic fields. 4 ms after the trap switch-off, a "push coil" is switched on for $\sim$240 ms, to create a magnetic field gradient to push magnetically sensitive atoms in a manner that prevents them from reaching the detector. The atoms are detected by a multi-channel plate and delay line (MCP-DLD) detector after ~ 416 ms of free-fall [7].

RESULTS

Following the method of [1], we extract a momentum profile from the reconstructed DLD data along the far-field vertical $\hat{z}$ direction using k space bins with integration volumes of $\Delta\theta = \pm 10^\circ$ and $\Delta k_\perp = \pm 0.8\ \mu\mathrm{m}^{-1}$, with θ the angle in the y-z plane from the z axis and $k_\perp$ the distance in k space along the $\hat{x}$ direction. The profile is only taken in a single direction from the BEC, i.e. only atoms are used that arrive at the detector after the arrival of the centre-of-mass of the BEC. This is to avoid unwanted background counts that are always present in low numbers when a magnetic trap is held above the detector, which we believe are due to Majorana flops and/or Penning ionisation. For an experiment like this where we are looking at extremely low count rates, such low rates become important. The data is averaged across a few thousand experimental sequences for each temperature, to resolve the low count rates in the quantum depletion tails. To minimise saturation effects on the detector, we keep the condensate density at the detector low.

Two such profiles are shown in Fig. 1. As in [1], three distinct regions can be seen: the BEC region, where the data follows a Thomas-Fermi profile (fit not shown), the thermal cloud (red shading), where the data fits a Bose-Einstein thermal distribution (dotted line), and a quantum depletion region (blue shading), where the data follows a power law distribution $k^{-\alpha}$ (dashed line). The fitted power law exponents are found to be $\alpha \approx 4$, consistent with [1].

From the power-law fits (blue region of the plots in Fig. 1), we are able to extract the contact constant C_∞, via the relation

$$n_\infty(k) = \frac{C_\infty}{(2\pi)^3\, k^\alpha}, \tag{1}$$

where C_∞ and α the free fit parameters. Given our detector quantum efficiency of $\sim 8(2)\%$ [8] and measured sweep transfer efficiency, we can simply count and scale to estimate the total number of condensed atoms N_0. Note that detector saturation might reduce this somewhat, although we endeavour to work in a regime where saturation effects are minimal. We can then determine the condensate density n_0 from the expression

$$n_0 = \frac{m\mu}{4\pi\hbar^2 a}, \tag{2}$$

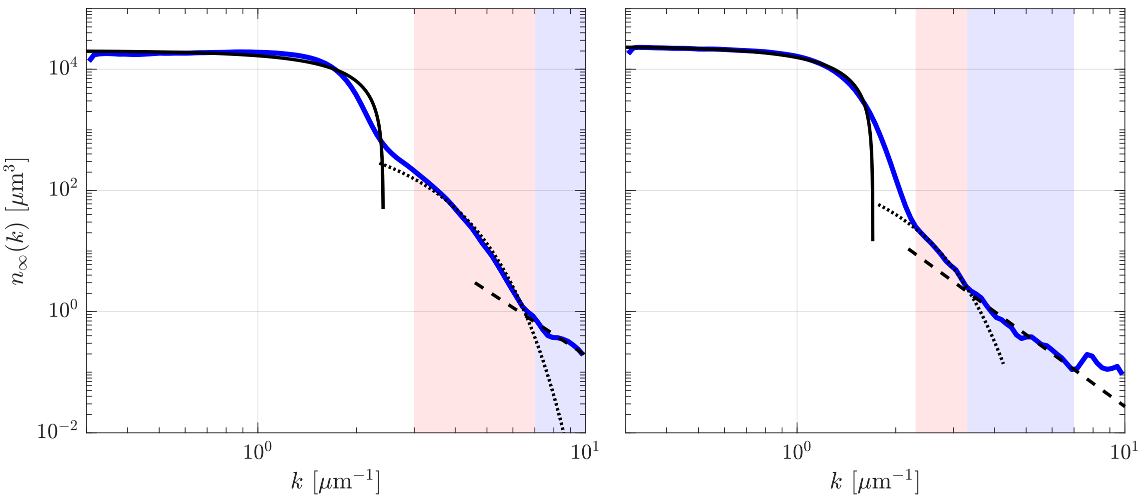

FIG. 1. Far-field k-space density profile of a magnetically trapped BEC, accounting for our detector efficiency and RF sweep transfer fraction (see text for details). Integration volumes are as described in the text. The left plot is for $T = 410(10)$ nK, and right plot is for $T = 150(10)$ nK (see text for full experimental parameters). Solid blue lines are smoothed 1D momentum density profiles measured from experiment. Solid black lines show a fit to a Thomas-Fermi distribution. The shaded red region is fitted with a thermal Bose distribution (dotted line), from which the temperatures are extracted. The shaded blue region is fitted with a $k^{-\alpha}$ power-law (dashed line) as expected for quantum depletion.

where μ is the chemical potential, m the mass of a helium atom and $a = 7.2$nm is the 2 body s-wave scattering length.

From these calculated parameters, we are able to plot the contact constant per condensed particle as a function of condensate density for two separate experimental datasets with different temperatures, shown in Fig. 2. We also plot a no free parameters fit of the theoretical prediction (solid line) given by Bogoliubov theory in the Local Density Approximation (LDA) of $C_{LDA}/N_0 n_0 = 5.08 \times 10^{-15} m^{-3}$ [1], which is slightly lower than the experimental values ($\sim$ a factor of 2), but is close to the errorbars. In [1], a significant discrepancy between theory and experiment was observed, but if the theory was scaled by a factor of 6.5, the two were seen to match again. However, as can be seen by the dashed line, such a scaling factor matches disagrees with our data. Even if there were some saturation unaccounted for in our detector, so that the atom number is underestimated, this would serve to further reduce our C_∞/N_0 values, increasing the discrepancy between our results and the previous work.

A summary of some important experimental parameters from each dataset are:

- $T = 410(10)$ nK, $N_0 = 3.6(6) \times 10^5, N_{th} = 6.2 \times 10^4$: $\alpha = 3.9(1)$ $n_0 = 22(5)\mu m^{-3}$ $C_\infty/N_0 = 0.21(18)$
- $T = 150(10)$ nK, $N_0 = 2.1(5) \times 10^5, N_{th} = 4.8 \times 10^3$: $\alpha = 3.5(3)$ $n_0 = 17(5)\mu m^{-3}$ $C_\infty/N_0 = 0.17(7)$

Note that the data reported in this document is preliminary, and hence several caveats need to be made. Firstly, to test the theory more thoroughly, more data is needed at a broader range of n_0, to confirm the linear trend over a larger region of parameter space. Also, the error bars and uncertainties throughout this document have been conservatively estimated. With a more careful error analysis they should be able to be reduced somewhat.

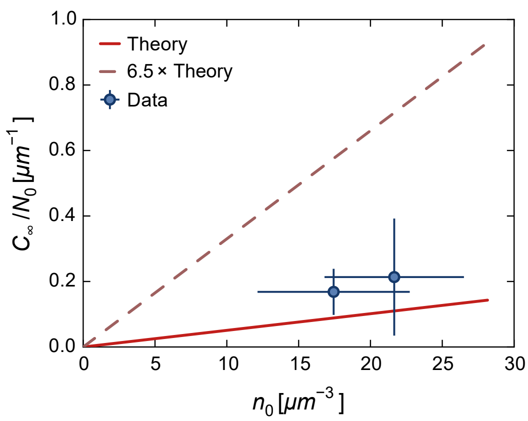

FIG. 2. Contact constant per condensed particle C_∞/N_0 plotted against BEC density n_0. Error bars show a combination of experimental uncertainties, fit error and shot-to-shot variations. The dominant sources are our atom number uncertainty, which is dominated by our quantum efficiency (QE) uncertainity, alongside fit uncertainties in extracting C_∞, due to only having limited data points to fit and it being unclear exactly where the fit should start and end. We estimate that our QE is 8(2)%. Theory lines are plotted as described in the main text. The red solid line is the prediction from Bogoliubov theory under the LDA approximation, while the dashed maroon line is 6.5$\times$ this.

CONCLUSION

Our experiment reproduces the results reported in [1] rather well, despite our trap switch-off being much slower. This suggests that the originally observed result is indeed a real physical effect. The main difference we observe is that we measure C_∞ coefficients that are much closer to the values predicted by Bogoliubov LDA theory, although still around two times higher. It is hard to see how the slower trap switch off could explain this observation, although perhaps this warrants closer investigation. Hopefully our result will stimulate new theoretical interest in developing an explanation of why the quantum depletion tails can be observed after an interacting expansion, as well as try to resolve the discrepancy with theory.

A possible future experimental extension is to outcouple atoms using a broadened Raman transition. This would have the benefit of moving the outcoupled atoms through the cloud rapidly, minimising the effects of repulsive interatomic interactions that normally affect the outcoupled profiles. This should shed some light on whether interactions during trap switch off are the origin of the momentum tails.

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[8] "We measure a quantum efficiency of our detector of $\sim 10\%$ through atom counting and comparing to the known number in the bec, while a lower bound on our detection efficiency is provided by a measured squeezing visibility in a collision halo of 7%. thus we quote our quantum efficiency as 8(2)%.".