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Density fluctuations in a very elongated Bose gas : transition towards quasi-bec and 1D-3D crossover

Isabelle Bouchoule, Julien Armijo, Thibaut Jacqmin and Karen
Kheruntsyan

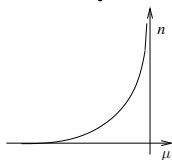
Institut d'Optique, Palaiseau.

Troyes, Août 2010



Weakly interacting Bose gases : 1D versus 3D behavior

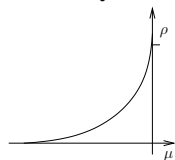
1D Physics



No BEC

Weakly interacting gas :
Smooth transition
towards quasi-bec
driven by interactions
Special case of correlated systems :
exact solutions

3D Physics



BEC phenomena : $\rho \lambda_{dB}^3 = 2.612\dots$



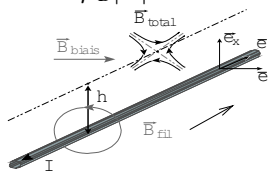
dimensional crossover

Realisation of very anisotropic traps on an atom chip

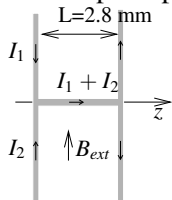
Magnetic confinement by micro-wires

^{87}Rb atoms in $F=2, m=2$

$$V = \mu_B |\mathbf{B}|$$

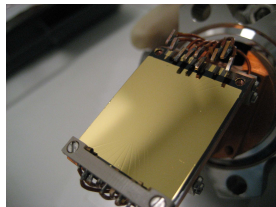
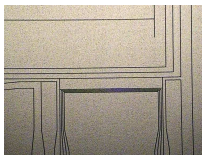
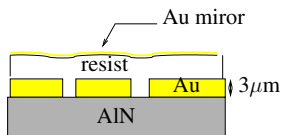


H-shape trap

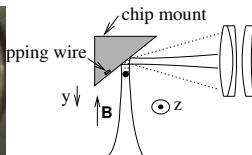
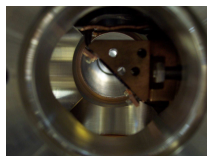


$$\begin{cases} \omega_{\perp}/2\pi = 3 \text{ kHz} \\ \omega_z/2\pi = 5 - 10 \text{ Hz} \end{cases}$$

The atom chip

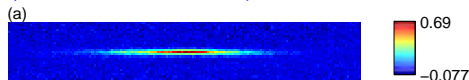


Experimental apparatus and sequence



- ^{87}Rb atoms loaded from a dispenser source in a MOT.
- Radio-frequency evaporative cooling in a magnetic trap
- Cycle time : 15 s

- Precise atomic profile measurement (absolute calibration)



$$T \simeq 400 - 15\text{nK}$$

$$\simeq 3.0 - 0.1\hbar\omega_{\perp}$$

$$N \simeq 5000 - 1000.$$

Density fluctuation measurements

- Statistical analysis over hundreds of images

$$l_c \ll \Delta \ll L$$

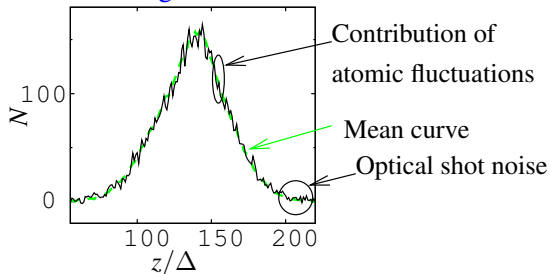
→ Local Density

Approximation valid

δN binned according to

$$\langle N \rangle$$

$\langle \delta N^2 \rangle$ versus $n = \langle N \rangle / \Delta$



→ Two-body correlation function integral

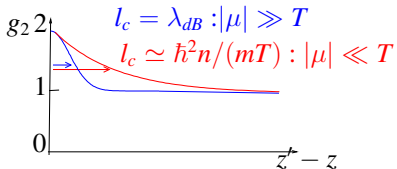
$$\langle \delta N^2 \rangle = \langle N \rangle + \langle N \rangle n \int dz (g_2(z) - 1)$$

→ Thermodynamic quantity

$$\langle \delta N^2 \rangle = k_B T \frac{\partial n}{\partial \mu}$$

Ideal Bose gas regime

- Bosonic bunching**



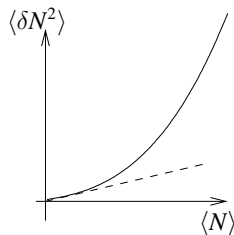
$$\langle \delta N^2 \rangle = \langle N \rangle + \underbrace{\langle N \rangle n \int dz (g_2(z) - 1)}_{l_c}$$

- Non degenerate gas : $n\lambda_{dB} \ll 1$

$$\begin{aligned} \langle \delta N^2 \rangle &= \langle N \rangle + \langle N \rangle n l c \\ &\simeq \langle N \rangle \end{aligned}$$

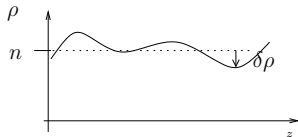
- Degenerate gas : $n\lambda_{dB} \gg 1$

$$\begin{aligned} \langle \delta N^2 \rangle &= \langle N \rangle + \langle N \rangle n l c \\ &\simeq \langle N \rangle^2 l c / \Delta \end{aligned}$$



Crossover towards quasi-condensate

- Repulsive Interactions \rightarrow Density fluctuations require energy



$$H_{int} = \frac{g}{2} \int dz \rho^2 \Rightarrow \delta H_{int} > 0$$

Reduction of density fluctuations at low temperature/high density

Cross-over : $\frac{1}{N} H_{int} \propto gn \simeq |\mu|$

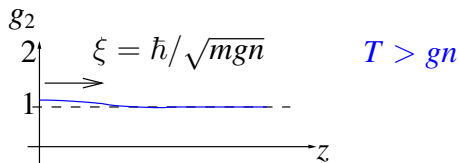
$$\Rightarrow T_{c.o.} \simeq \frac{\hbar^2 n^2}{2m} \sqrt{\gamma}, \quad n_{c.o.} \propto T^{2/3}$$

weakly interacting :
 $\gamma = mg/\hbar^2 n \ll 1$

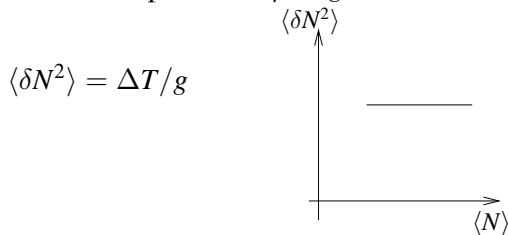
- For $T \ll T_{c.o.}$: quasi-bec regime, i.e. reduction of density fluctuations
- Transition occurs for degenerate gas ($\gamma \ll 1$)

Quasibec regime

- Bunching effect killed : $g_2(z)$ close to 1

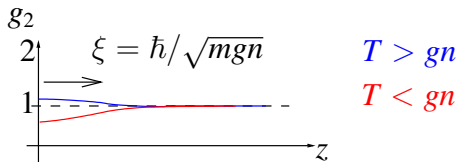


- Chemical potential : $\mu \simeq gn$

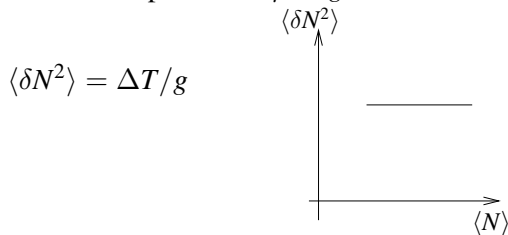


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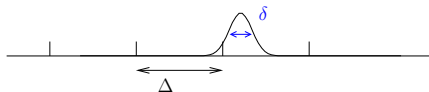
Effect of finite spatial resolution

- Absorption of an atom spreads on several pixels

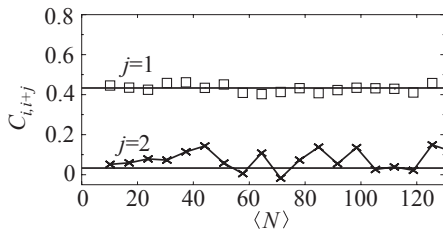
→ blurring of the image

Decrease of fluctuations :

$$\langle \delta N^2 \rangle = \kappa_2 \langle \delta N^2 \rangle_{\text{true}}$$



→ Correlation between pixels



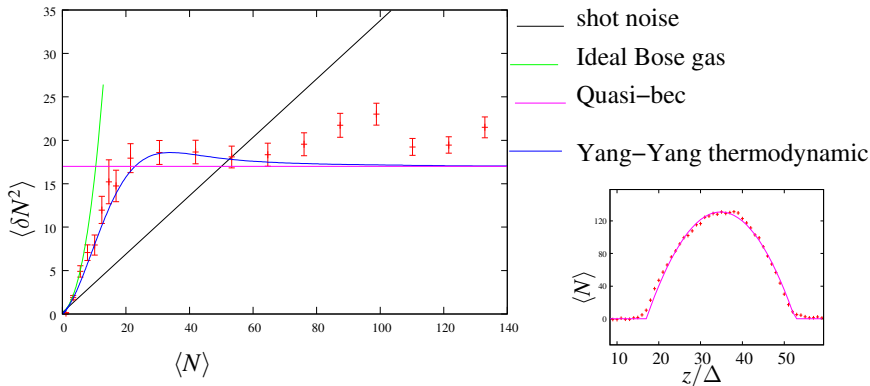
δ deduced from measured correlations between adjacent pixels

κ_2 deduced

Experimental results

$$T = 15 \text{ nK} \simeq \hbar\omega_{\perp}/10$$

$$\mu \simeq 30 \text{ nK} \simeq 0.2 \hbar\omega_{\perp}$$



- Strong bunching effect in the transition region
- Quasi-bec both in the thermal and quantum regime

1D-3D Crossover in the quasi-bec regime

$\mu \ll \hbar\omega_{\perp}$ ($na \ll 1$) \rightarrow Pure 1D quasi-bec

$\mu \gtrsim \hbar\omega_{\perp}$: 1D \rightarrow 3D behavior

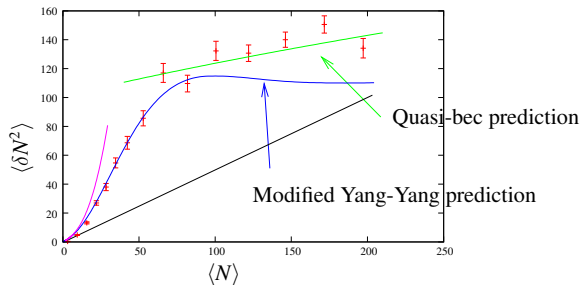
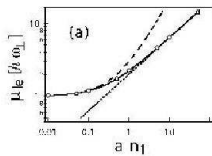
Transverse breathing associated with a longitudinal phonon has to be taken into account.

Thermodynamic argument : $\text{Var}(N) = k_B T \left(\frac{\partial N}{\partial \mu} \right)_T$

$$T = 96 \text{ nK} \simeq 0.5 \hbar\omega_{\perp}$$

Heuristic equation :

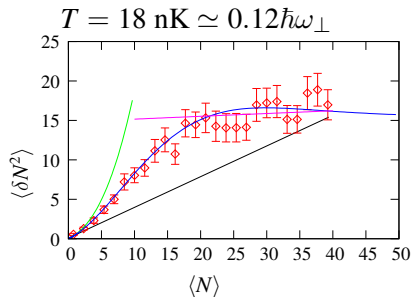
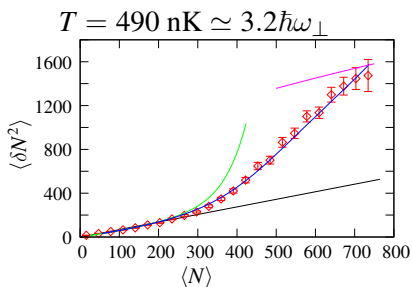
$$\mu = \hbar\omega_{\perp} \sqrt{1 + 4na}$$



Modified Yang-Yang model

Modified Yang-Yang model :

- Transverse ground state : Yang-Yang thermodynamic
- Excited transverse states : ideal 1D Bose gases



Surprisingly good agreement

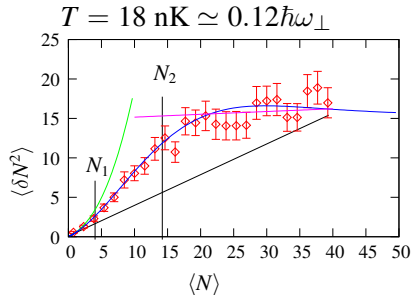
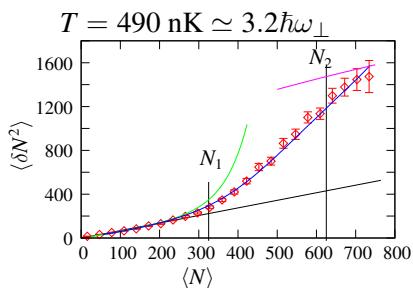
N_1 (resp. N_2) :

deviation from the ideal gas (resp. quasi-bec) model by 20%

Modified Yang-Yang model

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- Transverse ground state : Yang-Yang thermodynamic
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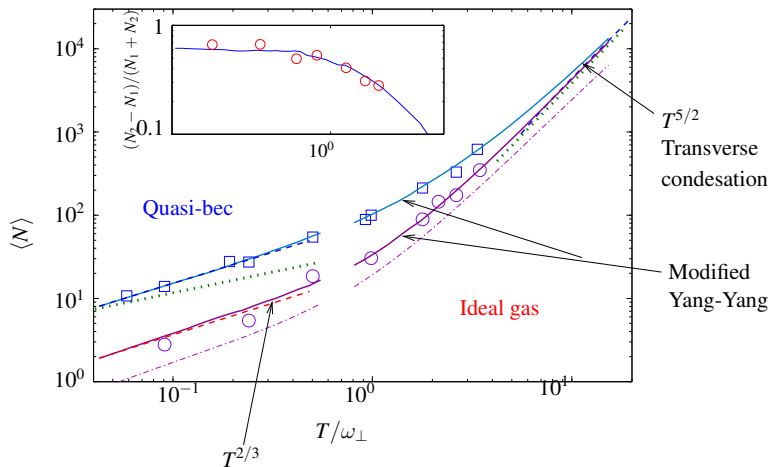


Surprisingly good agreement

N_1 (resp. N_2) :

deviation from the ideal gas (resp. quasi-bec) model by 20%

Quasi-bec transition in the 1D-3D crossover



Conclusion

Summary

- Investigation of the quasi-bec cross-over
- Highly 1D regime and crossover towards 3D
- 1D quasi-bec in the quantum fluctuations regime (subshotnoise)
- Non gaussian atom number distribution measured
- Evidence for three-body effect (strong cooling in the strongly 1D regime)

Prospect

- Study of correlation length of density fluctuations in 1D gases.
- 1D strongly interacting regime
- Localisation in strongly interacting 1D gases
- Momentum distribution/correlations