Use of a Delay-Line Detector for Prospection of Atomic Correlations in an Ultracold Gas

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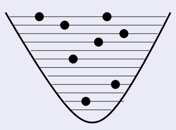
Introduction :

Direct measurement of the second order, or intensity, correlation function $G_2(\vec{r},\vec{r}')$ in quantum degenerate atomic samples is a still to achieve milestone in the cold atoms and Bose condensed atoms physics. In a pioneer work, Shimizu [2] showed that bosonic "hot" atoms tend to have the same bunching behavior as those of the thermal photons, just as happened in the known experiment due to Hanbury Brown and Twiss [3]. Shimizu's experiment did not, however, show the dependence of the second order coherence on the sample's temperature neither did it show the dramatic change in the quantum statistical properties when the sample comes to the vicinity of the Bose Einstein condensation[1].

In usual BEC experiments, the atom detection relies on optical imaging of the expanding clouds after the switching off of the magnetic or dipole traps. This kind of detection was, up to now, unable to detect single particles and that is the reason why the direct observation of the $G_2(\vec{r},\vec{r}')$ function remained yet unattended.

In contrast, our metastable helium Bose-Einstein Condensate in Orsay is well suited for this task. Here, to overcome the non existing permanent magnetic dipole moment of the fundamental *He* atom, needed to magnetic trapping, we are obliged to prepare it in a metastable triplet state. In this state the atom has a large internal energy of $20eV$, sufficient to extract an electron from a metallic surface, hence opening the door to single particle detection. So we can use a micro-channel plate (MCP) based detector for time of flight detection.

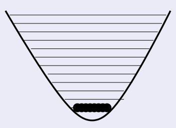
Atomic correlations :



Thermal gas: gaussian statistics

$$g^{(2)}_{trap}(\vec{r},\vec{r}') = 1 + |g^{(1)}(\vec{r},\vec{r}')|^2$$

where $g^{(1)}$ is a gaussian of width
$\lambda_T = \hbar\sqrt{2\pi/mk_BT}$: the thermal wavelength
Note: equivalent to photonic themal source



Bose-Einstein condensate:

$$g^{(2)}_{trap}(\vec{r},\vec{r}') = 1$$

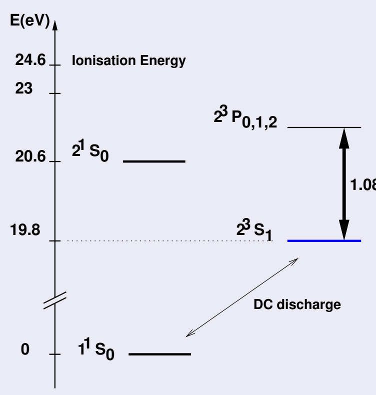
Note: equivalent to photonic laser source

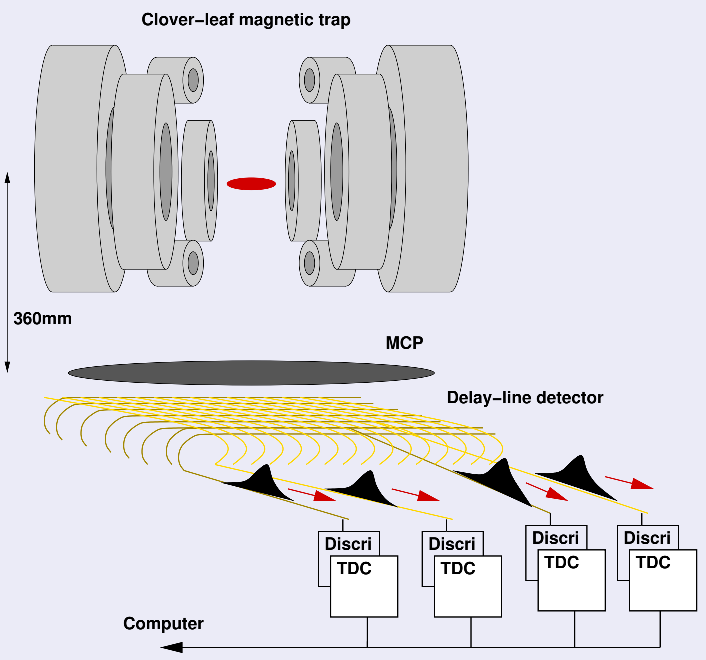
Experimental setup :

We use metastable Helium:
lifetime of 9000s,
20eV internal energy

- Necessary for trapping and laser cooling
- Allows electronic detection

The internal energy is indeed enough to extract electron from a metallic surface. Hence we can use a MCP for detection.





The atoms are trapped in a Ioffe-Pritchard magnetic trap. Magnetic polarisation inhibits Penning ionisation by 5 orders of magnitude, allowing thereby the evaporative cooling. When the trap is switched off, the atoms fall under gravity on the Micro-Channel Plate. This MCP produces a macroscopic electron flow (10^7) for each atom detected. Two delay-lines, combined to Time-to-Digital Converters, allow, by the means of a computer, to rebuild the Time of Flight in its three dimensions.

Expected correlations :

The atoms are detected after a long ToF ($t_{ToF} \gg \frac{trap\ size}{atoms\ speed}$). Hence we do not measure any trap position distribution: the ToF density rather translates the trap momentum distribution. Likewise we do not measure the trap space correlations, but rather the momentum correlations in the ToF. Simple phase-space conservation laws lead then to the following expectations:

- $x_{coh} = \lambda_T \omega_x t_{ToF}$
- $y_{coh} = \lambda_T \omega_y t_{ToF}$
- $t_{coh} = \frac{\lambda_T \omega_z}{g}$

with λ_T the DeBroglie wavelength, ω_i the trap frequency along the i axis, and g the gravity acceleration.

Note: On the$x$ and y axis we measure an in-the-end position correlation as a certain momentum gives a certain position after the ToF. Along the z axis the momentum changes the actual Time of Arrival on the detector: therefore we look for a time correlation on this axis.

Considering our experimental setup, this then leads to the following orders of magnitude:

- on X: $30\mu m$
- on Y: $600\mu m$
- on Z: $0.3ms$

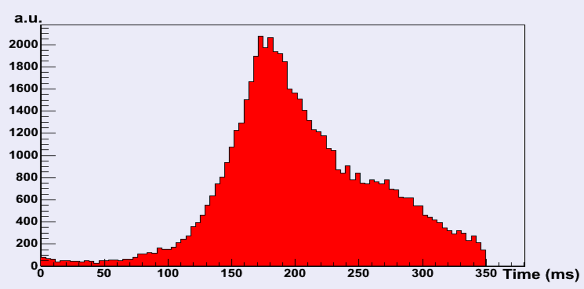
Signal to Noise :

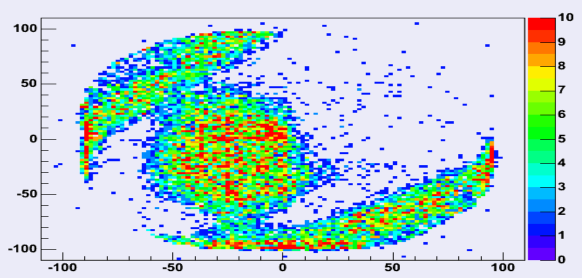
With a correlation area expected $30\mu m$ by $600\mu m$, compared to the $2\pi 4^2 cm^2$ detector size, the detector requires position sensitivity if we want an appreciable bunching excess. With a $400ps$ resolution TDC, we have a pixel resolution of $400\mu m$.

This makes correlation measurements on the x and y axis most unlikely, whereas the time correlation measurement brings no difficulty. Moreover, this resolution should give us a bunching excess of 5%, with a signal to noise ratio of 1 for a single run.

Preliminary results :

The delay-line detector is in place and works:





Those curves represent the ToF of a magnetic optical trap. The first graph is the time histogram of a total of 70.000 atoms being detected. In second place the x versus y graph has been plotted.

Two difficulties should yet be considered for the final experiment:

- As the latter graph already shows, magnetic or (here) optical pertubations can highly affect the not-so-short ToF.
- Under higher momentum densities, the MCP can show eventually severe saturation effects, which are still to be studied, and that could induce strong effective anti-correlations in a *ms* time-scale...

Yet those questions should soon be answered as the Bose-Einstein condensate seems just around the corner...

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