

# A Bose-Einstein Condensate of Metastable Atoms

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Bose-Einstein condensation (BEC) of helium in its ground electronic state has been known for decades and is responsible for many extraordinary properties of liquid helium. We have in our laboratory observed BEC of a helium gas, where the atomic state is the metastable triplet state ( $\text{He}^*$ ). Today, only one other group (the ENS group in Paris) has also observed this type of BEC [2].

A BEC of  $\text{He}^*$  is remarkable in that the constituent atoms contain a large internal energy: the  $2^3\text{S}_1$  state is 20 eV above the electronic ground state, and this energy is huge compared to the thermal energy of our sample ( $10^{-10}$  eV per atom at 1  $\mu\text{K}$ ). Only a complete decoupling of the internal and external degrees of freedom prevents conversion of the internal electronic atomic energy into ionization and kinetic energy that would lead to an immediate destruction of the condensate. An unpolarized sample of metastable helium at such a large density (about  $10^{13}\text{ cm}^{-3}$ ) would be destroyed in less than a millisecond [3, 4, 5]. The reason this does not happen is the complete spin polarization of a magnetically trapped gas. When all spins are aligned along the same direction, Penning ionizing collisions that could release the internal potential energy are suppressed by spin conservation [6].

The large energy content of each atom opens the ultimate possibility of detecting individual atoms with nanosecond time resolution, an extremely challenging task when using optical detection. When the atoms hit a detector such as a microchannel plate (MCP) with a velocity of 1 m/s as in our experiment, the time resolution translates into nanometer position resolution.

We show in Fig. 1 the signal from the MCP as a function of time after the atoms' release and for various values for the final frequency of the ramp. The time-of-flight (TOF) spectra show the arrival time distribution for a cloud of atoms falling on the detector. The figure shows that at a high final ramp frequency, *i.e.* above the condensation temperature, the spatial distribution is well approximated by a Maxwell-Boltzmann distribution, whereas when the ramp goes low enough, and reduces the temperature sufficiently, the distribution exhibits a narrow peak on top of a broad one. The fraction of atoms in the narrow peak increases as the final ramp frequency is lowered, and we interpret this peak as a BEC.

We have examined the behavior of the condensate for different atom numbers. Figure 2 shows the results of a series of runs for which the number of atoms in the condensate was varied. We plot the width corresponding to the Thomas-Fermi radius of the condensate after expansion, as a function of the number  $N_0$  of atoms in the condensed fraction. We obtained good fits to an inverted parabola squared for numbers of detected atoms as low as 400. The size  $w_i$  of the condensate in the direction  $i$ , in the Thomas-Fermi approximation, and for a

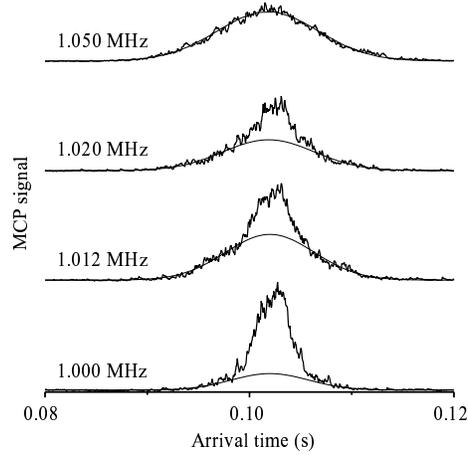


Figure 1: Time of flight spectra for different final frequencies of the RF-ramp (values at the left of each curve). The solid lines show Gaussian fits to the wings. This series of spectra shows the BEC transition as the RF-ramp lowers the temperature further and further. The temperature at the transition is  $0.7 \mu\text{K}$ . Each spectrum is a single-shot acquisition containing about  $5 \times 10^3$  atoms, although the actual number in the condensate is a factor of about 8 higher.

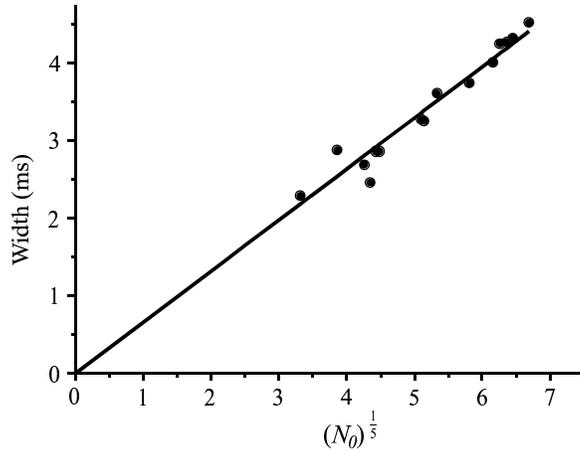


Figure 2: Observed width of the condensate peak after expansion, as a function of the number of atoms in the peak to the power  $1/5$ . The width is derived from the TOF spectrum, and is given in milliseconds. After correcting the number of atoms for the fraction we do not observe (see text), the slope of the straight line gives an estimate of the scattering length of  $20 \pm 10 \text{ nm}$ .

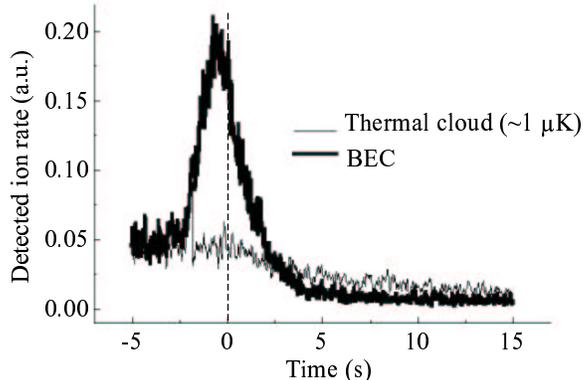


Figure 3: Ions detected by the MCP during the magnetic trap phase. The time  $t = 0$  corresponds to the end of the RF ramp. The thin line corresponds to a final RF frequency of 1.2 MHz (see Fig. 1) i.e. a thermal cloud ( $T = 1 \mu\text{K}$ ), whereas for 0.97 MHz (thick line) the cloud is almost a pure BEC. The life-time is smaller in the latter case indicating a higher loss rate for a BEC.

scattering length  $a$  is given by:

$$w_i = \sigma_i \sqrt{\frac{\tilde{\omega}}{\omega_i}} \left( 15 \frac{N_0 a}{\tilde{\sigma}} \right)^{1/5}$$

where  $\sigma_i = \sqrt{\hbar/m\omega_i}$  is the size of the ground state harmonic oscillator wavefunction along the  $i$ th direction, and  $\tilde{\sigma}$  denotes the geometric mean of the three sizes. To obtain the size of the condensate in the trap from the measured size after the expansion of  $t = 100$  ms, we use the analysis of [7] according to which, for a sudden switch off of the trapping potential, the spatial distribution of the condensate along an initially tightly confined direction  $i$  is simply dilated by a factor  $\omega_i t$  during expansion. Thus, the condensate size should vary as the  $1/5$  power of the number of atoms, as is confirmed by a fit to a Log-Log plot (slope 0.19) in figure 2.

Knowing the size as a function of the number of atoms in the condensate allows us also to get an estimate of the scattering length  $a$ . We used the data in figure 2, and obtained  $a = 20 \pm 10$  nm. This result is consistent with our elastic rate constant measurements at 1 mK [8].

We have also observed the ions produced by the trapped condensate by negatively biasing a grid above the MCP (Fig. 3). These ions are due to Penning ionization of residual gases, two-body Penning collisions within the condensate, or possibly other, more complicated processes. We observed a factor of four to five more ions from the condensate than from a thermal cloud at  $1 \mu\text{K}$ , and we attribute this increase to the larger density in the condensate. The lifetime of the condensate, estimated by observing the decay of the ion rate, is on the order of a few

seconds.

The observation of BEC in  $\text{He}^*$ , together with our MCP detector, offers many new possibilities for the investigation of BECs. The ion detection evoked in the previous paragraph allows continuous non-destructive monitoring of the trapped condensate. In this way, we plan to measure the real time formation of the condensate by observing the ion signal. Moreover, detection of individual atoms should allow one to perform accurate comparisons of correlation functions [9] for a thermal beam of ultracold atoms [10] and for an atom laser, realizing the quantum atom optics counterpart of one of the fundamental experiments of quantum optics. Experiments that are still unrealized in quantum photon optics may also become possible with a system like that reported here.

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