Reaching the hydrodynamic regime in a Bose-Einstein condensate by suppression of avalanches

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We report the realization of a Bose-Einstein condensate (BEC) in the hydrodynamic regime. The hydrodynamic regime is reached by evaporative cooling at a relatively low density suppressing the effect of avalanches. With the suppression of avalanches a BEC containing more than 10^8 atoms is produced. The collisional opacity can be tuned from the collisionless regime to a collisional opacity of more than 2 by compressing the trap after condensation. In the collisional opaque regime a significant heating of the cloud at time scales shorter than half of the radial trap period is measured, which is a direct proof that the BEC is hydrodynamic.

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The behavior of excitations in a BEC with energies larger than the mean field energy is determined by the mean free path of the atoms. Usually the mean free path of the atoms is larger than the size of the sample (the collisionless regime). However, it is of great interest to realize a BEC in the hydrodynamic regime, where the mean free path of the atoms is less than the size of the condensate. In this situation the properties of the BEC are strongly influenced by the inter-atomic collisions. A hydrodynamic BEC gives the opportunity to investigate interesting properties of the condensate, for example, thermal excitations, heat conduction, shape oscillations, when there is only local thermal equilibrium. A hydrodynamic BEC also provides the opportunity to study the phenomena of second sound experimentally.

The transition from the collisionless to the hydrodynamic regime above the BEC transition temperature has been studied theoretically [1] and experimentally [2]. For the situation below the BEC transition temperature several theoretical studies have been carried out regarding the frequencies and the damping rates of collective modes [3], the first and second sound modes [4], and the collisions between condensed and noncondensed atoms [5]. In this Letter we will discuss the experimental realization of a BEC in the hydrodynamic regime and the study of the excitations generated by three-body decay.

The most obvious way of reaching the hydrodynamic regime is creating a large and dense BEC. However, as shown in Ref. [6] the atomic losses will increase strongly due to avalanches at densities, that are normally necessary for entering the hydrodynamic regime. In a hydrodynamic BEC a high energy atom generated by a three-body collision will in general undergo additional collisions, before it leaves the sample, transferring his energy to other atoms. When the probability of a collision before leaving the sample is close to one, the chain of collisions becomes self sustaining. These avalanches will severely limit the lifetime of the condensate in the hydrodynamic regime, as well as the collisional opacity. Therefore, Schuster *et al.* [6] concluded that the collisionally opaque regime can hardly be reached in alkali BEC experiments. In the case of metastable helium BEC experiments to reach the hydrodynamic regime has so far been unsuccessful [7, 8]. A second way of realizing a hydrodynamic BEC is increasing the cross section for the elastic collisions by means of a Feshbach resonance. However, the increase in the cross section results in a large loss rate [9], which makes it an unsuitable approach for achieving a hydrodynamic BEC. Notable exceptions are the BEC's of molecules consisting of fermions tuned close to the unitarity limit [10].

In this Letter we will show that it is possible to enter the hydrodynamic regime by following the first approach with a strong reduction of the effects of the problems mentioned above. This is done by evaporative cooling a cloud of sodium atoms to the BEC temperature in a decompressed trap. The low trap frequencies lead to a relatively low density of the cloud, which reduces the onset of avalanches. The suppression of avalanches results in our setup in a BEC containing more than 10^8 sodium atoms at a density of 2.7×10^{14} atoms/cm^3. The low density suppresses the losses as a result of avalanches, while the large physical size of the BEC results in a collisional opacity close to the hydrodynamic limit. The hydrodynamic regime can subsequently be entered deeply by compressing the trap after BEC is reached.

During the evaporation towards the BEC transition the cloud of atoms will experience losses due to inelastic collisions between atoms. These losses can be divided into three categories: one-, two- and three-body collisions, determined by the rate constants $G_{1,2,3}$. The one- and two-body collisions do not play a dominant role in our case due to the low background pressure and the relatively small G_2 coefficient, respectively. The dominant loss process is three-body collisions and the loss rate for this process is given by G_3n^2 with $G_3 = 1.1\times10^{-30}$ cm^6/s [12]. The three-body collisions generate high energy atoms that will in the collisionless regime be removed from the trap by evaporation before they rethermalize. However, when the sample is in the hydrodynamic regime, the high energy atom will collide with other atoms before it leaves the trap resulting in an

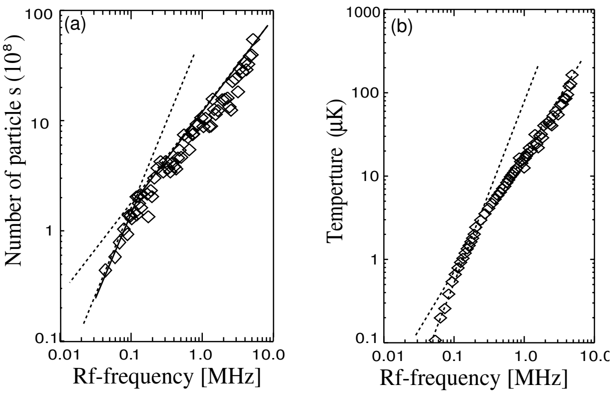

FIG. 1: (a) Number of atoms and (b) the temperature for evaporative cooling as a function of the rf-frequency with respect to the bottom of the trap. The dotted lines are a guide to the eye indicating a decrease in the efficiency below a rf-frequency of 200 kHz.

avalanche. In that case a large fraction of the energy generated by a three-body decay is released into the BEC resulting in a large loss rate of atoms and a strong heating of the sample. By contrast, in the collisionless regime only 3 atoms are lost without heating the sample. This striking difference in thermal properties makes the hydrodynamic regime very interesting, but extremely hard to reach.

We start the experiment with a magneto-optical trap (MOT) containing 2.0×10^{10} sodium atoms. After spin-polarizing in a strong magnetic field 1.4×10^{10} atoms are loaded in a cloverleaf magnetic trap (MT). The magnetic field gradient of 118 Gauss/cm in the radial direction and the curvature field of 42 G/cm^2 in the axial direction lead to trap frequencies in the axial and radial direction of ν_z = 16 Hz and ν_ρ = 99 Hz at a field minimum of 3.4 G. We can cool the sample of atoms to degeneracy in 50 seconds. After turning off the MT followed by a ballistic expansion, the sample of atoms is imaged by absorption imaging. The data is fitted using a bimodal distribution with a Gaussian profile for the thermal atoms combined with a Thomas-Fermi profile for the condensed atoms. The parameters of the Gaussian profile yield the number particles and the temperature of the thermal part, while the parameters of the Thomas-Fermi profile yield the chemical potential, from which the number of condensed atoms is determined. A more detailed description of the experimental setup is presented in Ref. [13, 14].

In Fig. 1 the number of particles and the temperature of the cloud as a function of the rf-frequency is shown. The data indicate a decreasing efficiency parameter $\alpha = (\dot{T}/T)/(\dot{N}/N)$ below 200 kHz. The density at this point in the evaporation is $(7\pm1)\times10^{13}$ atoms/cm^3, which is close to the density, where the three-body losses become the dominant loss process. Despite the large loss rate we can still condense 0.35×10^8 atoms at a density of 4.0×10^{14} atoms/cm^3.

The collisional opacity is defined as $\kappa = \langle nr\rangle\,\sigma_s$, with $\sigma_s = 8\pi a^2$ the s-wave cross section, a the scattering length, and $\langle nr\rangle$ the average column density [6]. Under the conditions of Fig. 1 the collisional opacity κ of the BEC is 0.88, which means that the mean free path of an atom in the condensate is of the same order than its size making the BEC almost hydrodynamic. However, for a thorough investigation of the hydrodynamics of the BEC it is necessary to enter the hydrodynamic regime deeper. To achieve this, a BEC containing more atoms without increasing the density is needed. This is realized by suppressing the losses due to three-body collisions during the evaporation. Since the three-body losses scale quadratically with density, this suppression is achieved by reducing the density. Therefore, the trap is decompressed after 42 seconds of evaporation, which corresponds with an rf-frequency of 2.04 MHz with respect to the bottom of the trap. The decompression is done adiabatically in 2 s. At higher frequencies three-body losses are not the limiting loss process because the density is always below 2×10^{13} atoms/cm^3 yielding a loss rate of 4×10^{-4}/s. For the decompression the trap frequencies can be lowered in either axial or radial direction.

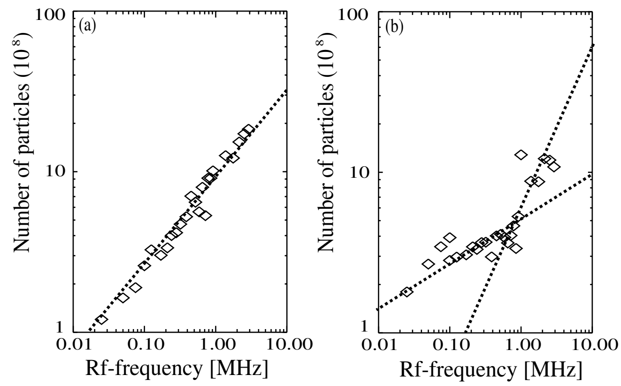

FIG. 2: The number of particles during the evaporation in a radial decompressed trap (a) and in an axial decompressed trap (b). The dotted lines are a guide to the eye.

In Fig. 2a the number of particles during the evaporative cooling is shown for a radial decompressed trap. The radial trap frequency is in this case lowered from 99 Hz to 50 Hz resulting in an average trap frequency $\bar{\omega} \equiv \sqrt[3]{\omega_r\omega_r\omega_z} = 34$ Hz. Combined with the results of the temperature as a function of rf-frequency we observe no decrease in efficiency. The evaporation in this trap results in a BEC containing 0.6×10^8 atoms at a density of 2.7×10^{14} atoms/cm^3.

When the decompression takes place in the axial direction (16 Hz $\rightarrow$ 4 Hz) instead of the radial direction, the efficiency is even higher (Fig. 2b). Note, that this decompression results in the same average trap frequency $\bar{\omega}$ as above and thus the same decrease in density. The evaporation in the axial decompressed trap leads to more than 10^8 atoms in the BEC. This is as far as we know the largest condensate starting from an optical trap. Note, that we lose less than a factor of 150 in the number of

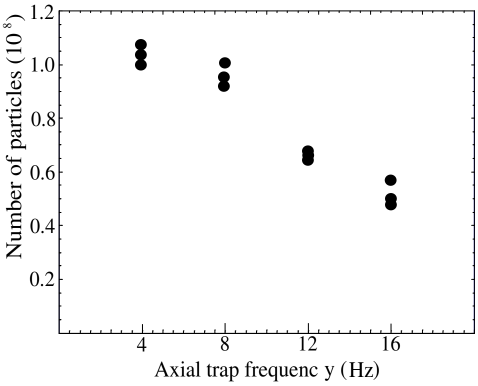

FIG. 3: The number of particles in the BEC as a function of the axial trap frequency with $\bar{\omega} = 34$ Hz.

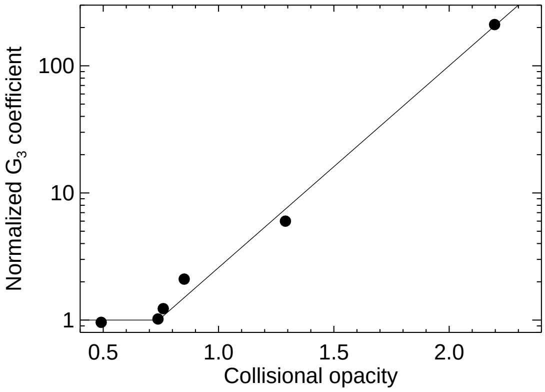

FIG. 4: The increase in G_3 coefficient as a function of the collisional opacity κ. The determined G_3 coefficient is normalized to the G_3 coefficient in the collisionless regime [12]. The solid line is a guide to the eye.

atoms during the evaporation indicating an efficient suppression of the loss rate. The increase in the efficiency parameter α indicated in Fig. 2b by the dotted lines suggests that an earlier decompression would even lead to more condensed atoms. However, by carefully optimizing the sequence it turned out that the decompression after 42 s of evaporation leads to the largest number of atoms.

In Fig. 3 the results of a quantitative analysis of decompression are given. In this figure the number of atoms in the BEC is plotted for different decompression scenarios. The radial trap frequency is adjusted in such a way that for every measurement the average trap frequency is kept constant ($\bar{\omega} = 34$ Hz). The number of particles shows a monotone increasing behavior with decreasing axial trap frequency. In all cases, the initial temperature, density and therefore, three-body collision rate are identical. The only difference is the aspect ratio of the cloud. In the radial decompressed trap the collisional opacity κ is larger and thus atoms undergoing a three-body collision are more likely to generate avalanches. Furthermore, a large κ can hamper the evaporative cooling. Either way, these measurements are a clear sign that we have reached the hydrodynamic regime. In the axial decompressed trap the avalanches are suppressed, until BEC is reached. At the BEC transition the collisional opacity has increased to 0.74 resulting in a BEC at the cross-over between the collisionless and the hydrodynamic regime.

Above we have described how a large atom number BEC with κ close to 1 is realized by suppression of avalanches. After the BEC transition is reached κ can be tuned from the collisionless regime to a value of 2.2 by compressing the trap in axial direction in 100 ms. In the remainder of this Letter the adjustability of κ is used for two kind of experiments. First, the influence of the avalanches on the loss rate is investigated. Second, a direct proof of the hydrodynamics is presented for $\kappa = 2.2$ by studying the heating due to avalanches.

Previous work [6] has shown that the lifetime of a BEC in the hydrodynamic regime is severely limited by avalanches. In this experiment the avalanches increases the G_3 coefficient by a factor of 8. We have measured the G_3 coefficient as a function of κ (Fig. 4). For each value of κ the G_3 coefficient is determined from the lifetime of the BEC. As seen from Fig. 4, the G_3 coefficient increases with more than two orders of magnitude by increasing κ. At collisional opacities below 0.7 the loss rate is determined by the G_3 coefficient characteristic for the collisionless regime, indicating that there are no avalanches. The energy of a three-body decay is in the order of 3000 T_c, where T_c is the critical temperature for BEC. So it is expected that the G_3 coefficient will increase even further with increasing κ. In our experiment we are not able to compress the MT further or to condense more atoms, so we can not determine an upper limit for G_3.

When the trap is fully compressed after reaching the BEC transition $\kappa = 2.2$ is reached at a density of 6.6×10^{14} atoms/cm^3. The increased density due to the compression and the effect of the avalanches result in a reduction of the lifetime to below 20 ms. The lifetime is sufficient for several experiments like second sound, which takes 10 to 50 ms to propagate through the sample. Furthermore, the lifetime can be increased significantly by tuning the BEC to a slightly lower collisional opacity. This is shown in Fig. 5, where the lifetime of the BEC in the hydrodynamic regime is studied in more detail by measuring the number of particles in the BEC as a function of the storage time for a hydrodynamic BEC with $\kappa = 1.3$ (circles), and a BEC in the collisionless regime with $\kappa = 0.74$ (squares). During the storage time an rf-shield is applied at 100 kHz generating a trap depth of 5 μK to avoid strong heating. The lifetime of the condensate in the hydrodynamic and collisionless regime is 10 and 20 s, respectively. The horizontal lines indicate the number of particles needed for $\kappa = 1.0$. Note, that the crossover between the hydrodynamic and collisionless regime is different for the two situations, because the trap

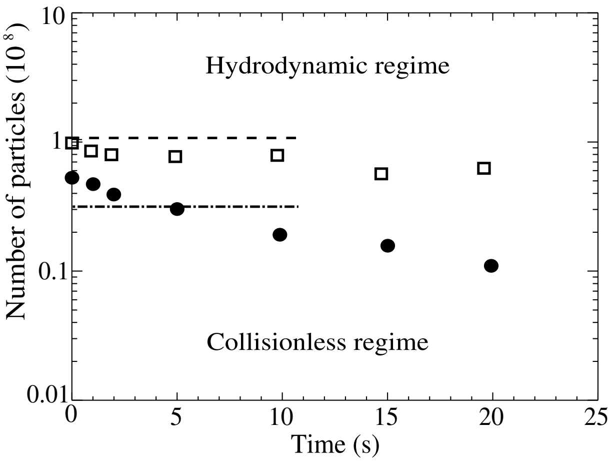

FIG. 5: The number of particles in the BEC as a function of the storage time for a hydrodynamic BEC with $\kappa = 1.7$ (circles), and a BEC in the collisionless regime with $\kappa = 0.8$ (squares). The horizontal lines indicates $\kappa = 1$.

frequencies are different. We can see that the hydrodynamic BEC stays in the hydrodynamic regime for more than 5 s, which is an increase with more than a factor of 25 compared to earlier work [6]. The hydrodynamic BEC is in this case produced with radial decompression during the evaporation, showing that we can evaporative cool in the hydrodynamic regime. Since the losses are larger during the cooling the BEC contains less atoms. Note, that the decay of the hydrodynamic BEC is much faster at small time scales indicating avalanche enhanced losses.

The collisional opacity of 2.2 results in a s-wave collision probability of 0.89. This means that an atom has chance of 89% to collide with another atom, while traveling through the condensate. In this situation a significant fraction of the energy generated by a three-body collision is distributed over the BEC on a time scale faster than half the radial trap period which is 5 ms in our case. When we measure the temperature of the strongly hydrodynamic sample as a function of the storage time we see an increase of the temperature due to heating of more than 35% within 4 ms (Fig. 6). This is a direct proof that the BEC is deeply in the hydrodynamic regime. This heating is not significantly suppressed by the rf-shield. Note that the relatively slow compression (100 ms) has only a limited effect on the collisional opacity of the BEC, because the large heating rate only occurs very close to the final value of κ.

In this Letter we have described the experimental realization of a hydrodynamic BEC. This is achieved by suppressing the avalanches during the evaporation towards the BEC transition resulting in a BEC containing more than 10^8 sodium atoms with a collisional opacity of 0.74. The collisional opacity is low enough to suppress the avalanches during generation of the BEC, while it is high enough to yield the possibility to enter the hydrodynamic regime deeply by compressing the trap, after the BEC transition is reached. The collisional opacity can be tuned from the collisionless to the hydrodynamic regime with a collisional opacity of 2.2 by axial compression. Furthermore, the lifetime of the BEC in the hydrodynamic regime is more than 5 s, which makes it a very good starting point for further research on the hydrodynamic behavior of the BEC.

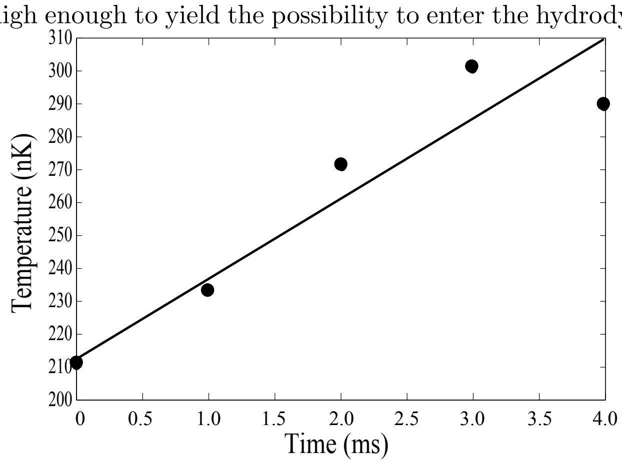

FIG. 6: The heating of the sample for a strongly hydrodynamic BEC with $\kappa = 2.2$.

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