Quasipure Bose-Einstein Condensate Immersed in a Fermi Sea

F. Schreck, L. Khaykovich, K. L. Corwin, G. Ferrari,* T. Bourdel, J. Cubizolles, and C. Salomon

Laboratoire Kastler Brossel, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris CEDEX 05, France
(Received 13 July 2001; published 7 August 2001)

We report the observation of coexisting Bose-Einstein condensate (BEC) and Fermi gas in a magnetic trap. With a very small fraction of thermal atoms, the ^{7}Li condensate is quasipure and in thermal contact with a ^{6}Li Fermi gas. The lowest common temperature is 0.28 μK $\simeq 0.2(1)T_C = 0.2(1)T_F$ where T_C is the BEC critical temperature and T_F the Fermi temperature. The ^{7}Li condensate has a one-dimensional character.

Bose-Einstein condensation (BEC) of atomic gases has been very actively studied in recent years [1,2]. The dilute character of the samples and the ability to control the atom-atom interactions allowed a detailed comparison with the theories of quantum gases. Atomic Fermi gases, on the other hand, have only been investigated experimentally for two years [3–5]. They are predicted to possess intriguing properties and may offer an interesting link with the behavior of electrons in metals and semiconductors, and the possibility of Cooper pairing [6] such as in superconductors and neutron stars. Mixtures of bosonic and fermionic quantum systems, with the prominent example of ^{4}He-^{3}He fluids, have also stimulated intense theoretical and experimental activity [7]. This has led to new physical effects including phase separation, influence of the superfluidity of the Bose system on the Fermi degeneracy, and to new applications such as the dilution refrigerator [7–9].

In this paper, we present a new mixture of bosonic and fermionic systems, a stable Bose-condensed gas of ^{7}Li atoms in the internal state $|F = 1, m_F = -1\rangle$ immersed in a Fermi sea of ^{6}Li atoms in $|F = 1/2, m_F = -1/2\rangle$ (Fig. 1). Confined in the same magnetic trap, both atomic species are in thermal equilibrium with a temperature of $0.2(1)T_F \ll T_C$. All previous experiments performed with ^{7}Li in $|F = 2, m_F = 2\rangle$ had condensate numbers limited to $N \le 1400$ because of the negative scattering length, $a = -1.4$ nm, in this state [10,11]. Our condensate is produced in a state which has a positive, but small, scattering length, $a = +0.27$ nm [12]. The number of condensed atoms is typically 10^4, and BEC appears unambiguously both in the position distribution in the trap and in the standard time of flight images.

Because of the symmetrization postulate, colliding fermions have no s-wave scattering at low energy. In the low temperature domain of interest, the p-wave contribution vanishes. Our method for producing simultaneous quantum degeneracy for both isotopes of lithium is sympathetic cooling [4,5]; s-wave collisions between two different atomic isotopes are allowed and rf evaporation selectively removes from the trap high energy atoms of one species. Elastic collisions subsequently restore thermal equilibrium of the two-component gas at a lower temperature.

Our experimental setup has been described in detail in [4,13]. A mixture of ^{6}Li and ^{7}Li atoms is loaded from a magneto-optical trap into a strongly confining Ioffe-Pritchard trap at a temperature of about 2 mK. As depicted in Fig. 1, this relatively high temperature precludes direct magnetic trapping of the atoms in their lower hyperfine state because of the shallow magnetic trap depth, 2.4 mK for ^{7}Li in $|F = 1, m_F = -1\rangle$ and 0.2 mK for ^{6}Li in $|F = 1/2, m_F = -1/2\rangle$. Therefore we proceed in two steps. Both isotopes are first trapped and cooled in their upper hyperfine states. The ^{7}Li $|F = 2, m_F = 2\rangle$ and ^{6}Li $|F = 3/2, m_F = 3/2\rangle$ states have no energy maximum as a function of the magnetic field (Fig. 1). Thus the trap depth can be large. Evaporation is performed selectively on ^{7}Li using a microwave field near 803 MHz that couples $|F = 2, m_F = 2\rangle$ to $|F = 1, m_F = 1\rangle$. When both gases are cooled to a common temperature of about 9 μK, atoms are transferred using a combination of microwave and rf pulses into states $|F = 1, m_F = -1\rangle$ and $|F = 1/2, m_F = -1/2\rangle$ with an energy far below their respective trap depths. Evaporative cooling is then resumed until ^{7}Li reaches the BEC threshold.

In the first series of experiments, both Li isotopes are trapped in their higher hf states. ^{6}Li is sympathetically cooled to Fermi degeneracy by performing 30 s of

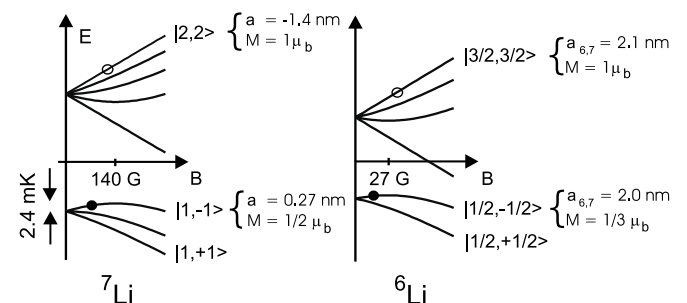FIG. 1. Energy levels of ^{7}Li and ^{6}Li ground states in a magnetic field. Relevant scattering lengths, a, and magnetic moments, M, are given. μ_b is the Bohr magneton. The $|1, -1\rangle$ state (respectively, $|1/2, -1/2\rangle$) is trapped only in fields weaker than 140 G (respectively, 27 G). Open circles: first cooling stage; black circles: second cooling stage.

evaporative cooling on ^{7}Li [4]. Trap frequencies for ^{7}Li are $\omega_{\text{rad}} = 2\pi \times 4000(10)$ s^{-1} and $\omega_{\text{ax}} = 2\pi \times 75.0(1)$ s^{-1} with a bias field of 2 G. Absorption images of both isotopes are recorded on a single CCD camera with a resolution of 10 μm. Images are taken quasisimultaneously (only 1 ms apart) in the trap or after a time of flight expansion. Probe beams have an intensity below saturation and a common duration of 30 μs. Typical *in situ* absorption images in the quantum regime can be seen in Fig. 2. Here the temperature T is 1.4(1) μK and $T/T_F = 0.33(5)$, where the Fermi temperature T_F is $(\hbar\bar{\omega}/k_B)(6N_F)^{1/3}$, with $\bar{\omega}$ the geometric mean of the three oscillation frequencies in the trap and N_F the number of fermions. For images recorded in the magnetic trap, the common temperature is measured from the spatial extent of the bosonic cloud in the axial direction since the shape of the Fermi cloud is much less sensitive to temperature changes when $T/T_F < 1$ [14]. The spatial distributions of bosons and fermions are recorded after a 1 s thermalization stage at the end of the evaporation. As the measured thermalization time constant between the two gases, 0.15 s, is much shorter than 1 s, the two clouds are in thermal equilibrium [15]. Both isotopes experience the same trapping potential. Thus the striking difference between the sizes of the Fermi and Bose gases [5] is a direct consequence of Fermi pressure. The measured axial profiles in Fig. 2 are in excellent agreement with the calculated ones (solid lines) for a Bose distribution at the critical temperature T_C. In our steepest traps, Fermi temperatures as high as 11 μK with a degeneracy of $T/T_F = 0.36$ are obtained. This T_F is a factor of 3 larger than the single photon recoil temperature at 671 nm, opening interesting possibilities for light scattering experiments [16].
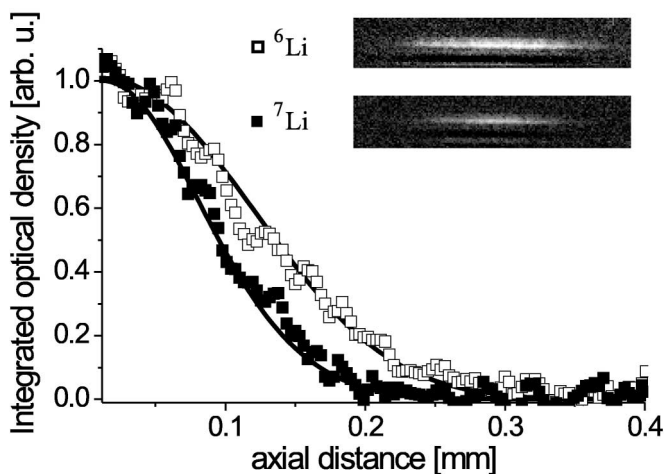
Our highest Fermi degeneracy in ^{6}Li $|F = 3/2, m_F = 3/2\rangle$, achieved by cooling with ^{7}Li $|F = 2, m_F = 2\rangle$, is $T/T_F = 0.25(5)$ with $T_F = 4$ μK, very similar to Ref. [5]. We observe that the boson temperature cannot be lowered below T_C. Indeed, because of the negative scattering length in ^{7}Li $|F = 2, m_F = 2\rangle$, for our trap parameters, collapse of the condensate occurs when its number reaches ~ 300 [10]. Since sympathetic cooling stops when the heat capacity of the bosons becomes lower than that of the fermions, this limits the Fermi degeneracy to about 0.3 [5].

In order to explore the behavior of a Fermi sea in the presence of a BEC with a temperature well below T_C, we perform another series of experiments with both isotopes trapped in their lower hf state where the positive ^{7}Li scattering length (Fig. 1) allows the formation of a stable BEC with high atom numbers. To avoid large dipolar relaxation, ^{6}Li must also be in its lower hf state [17]. First, sympathetic cooling down to ~ 9 μK is performed on the ^{7}Li $|F = 2, m_F = 2\rangle$, ^{6}Li $|F = 3/2, m_F = 3/2\rangle$ mixture as before. Then, to facilitate state transfer, the trap is adiabatically opened to frequencies $\omega_{\text{rad}} = 2\pi \times 100$ s^{-1} and $\omega_{\text{ax}} = 2\pi \times 5$ s^{-1} (for ^{7}Li, $F = 2$).

The transfer of each isotope uses two radio frequency π pulses. The first pulse at 803 MHz for ^{7}Li (228 MHz for ^{6}Li) transfers the bosons from $|2, 2\rangle$ to $|1, 1\rangle$ (the fermions from $|3/2, 3/2\rangle$ to $|1/2, 1/2\rangle$). These states are magnetically untrapped states (see Fig. 1). The second π pulse at 1 MHz for ^{7}Li (1.3 MHz for ^{6}Li) transfers the bosons to $|1, -1\rangle$, a magnetically trapped state (the fermions to $|1/2, -1/2\rangle$). Adiabatic opening of the trap cools the cloud. It decreases the energy broadening of the resonance and gives more time for the passage through untrapped states. The durations of the π pulses are 17 and 13 μs and more than 70% of each isotope is transferred. Finally the trap is adiabatically recompressed to the steepest confinement giving $\omega_{\text{rad}} = 2\pi \times 4970(10)$ s^{-1} and $\omega_{\text{ax}} = 2\pi \times 83(1)$ s^{-1} for ^{7}Li $|F = 1, m_F = -1\rangle$, compensating for the reduced magnetic moment.

Because of the very large reduction of the ^{7}Li s-wave scattering cross section from the $F = 2$ to the $F = 1$ state (a factor ~ 27 [17]), we were unable to reach runaway evaporation with ^{7}Li atoms alone in $F = 1$. In contrast, the ^{6}Li/^{7}Li cross section is ~ 27 times higher than the ^{7}Li/^{7}Li one [12,17]. We therefore use ^{6}Li atoms as a mediating gas to increase the thermalization rate of both gases. Two different methods were used to perform the evaporation. The first consists of using two rf ramps on the hf transitions of ^{6}Li (from $|1/2, -1/2\rangle$ to $|3/2, -3/2\rangle$) and ^{7}Li (from $|1, -1\rangle$ to $|2, -2\rangle$), which we balanced to maintain roughly equal numbers of both isotopes. After 10 s of evaporative cooling, Bose-Einstein condensation of ^{7}Li occurs together with a ^{6}Li degenerate Fermi gas (Fig. 3). Surprisingly, a single 25 s ramp performed only on ^{6}Li achieved the same results. In this case the equal number condition was fulfilled because of the reduced lifetime of the ^{7}Li cloud that we attribute to dipolar collisional loss [17]. The duration of the rf evaporation was matched to

FIG. 2. Observation of Fermi pressure. Absorption images in the trap and spatial distributions integrated over the vertical direction of 8.1×10^4 ^{6}Li and 2.7×10^4 ^{7}Li atoms in their higher hyperfine states. The temperature is 1.4(1) μK = 1.1(2)T_C for the bosons and 0.33(5)T_F for the fermions. Solid lines are the expected Bose and Fermi distributions.
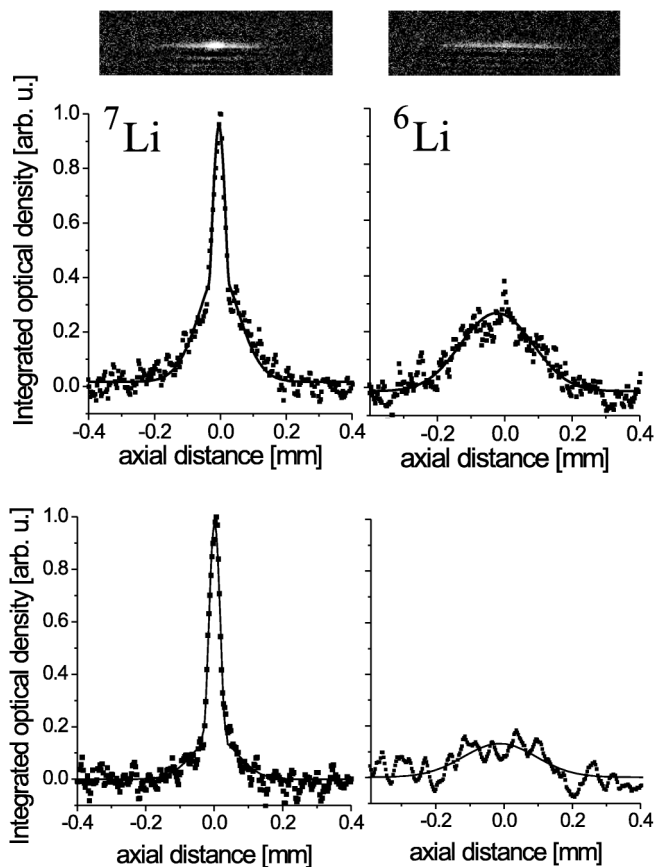
FIG. 3.   Mixture of Bose and Fermi gases. Top: *In situ* spatial distributions after sympathetic cooling with $N_B = 3.5 \times 10^4$ and $N_F = 2.5 \times 10^4$. The Bose condensed peak (8.5×10^3 atoms) is surrounded by the thermal cloud which allows the determination of the common temperature: $T = 1.6 \, \mu K = 0.87 T_C = 0.57 T_F$. The Fermi distribution is wider because of the smaller magnetic moment and Fermi pressure. Bottom: profiles with a *quasipure* condensate, with $N_B = 10^4$, $N_F = 4 \times 10^3$. The barely detectable thermal cloud indicates a temperature of $\simeq 0.28 \, \mu K \simeq 0.2(1) T_C = 0.2(1) T_F$.

this loss rate. In the following we concentrate on this second, and simpler, evaporation scheme, sympathetic cooling of ^{7}Li by evaporative cooling of ^{6}Li.

In Fig. 3 *in situ* absorption images of bosons and fermions at the end of the evaporation are shown. The bosonic distribution shows the typical double structure: a strong and narrow peak forms the condensate at the center, surrounded by a much broader distribution, the thermal cloud. As the Fermi distribution is very insensitive to temperature, this thermal cloud is a very useful tool for the determination of the common temperature. Note that, as cooling was performed only on ^{6}Li atoms, the temperature measured on ^{7}Li cannot be lower than the temperature of the fermions. Measuring N_B, N_F, the condensate fraction N_0/N_B, and $\bar{\omega}$, we determine the quantum degeneracy of the Bose and Fermi gases. In Fig. 3 (top), the temperature is just below T_C, $T = 1.6 \, \mu K = 0.87 T_C = 0.57 T_F$. In Fig. 3 (bottom) on the contrary, the condensate is quasipure; $N_0/N_B = 0.77$; the thermal fraction is near our detectivity limit, indicating a temperature of $\simeq 0.28 \, \mu K \leq 0.2 T_C =$

$0.2(1) T_F$ with $N_B = 10^4$ bosons and 4×10^3 fermions. The condensate fraction N_0/N_B as a function of T/T_C is shown in Fig. 4(a), while the size of the fermi gas as a function of T/T_F is shown in Fig. 4(b). With the strong anisotropy ($\omega_{rad}/\omega_{ax} = 59$) of our trap, the theory including anisotropy and finite number effects differs significantly from the thermodynamic limit [2], in agreement with our measurements even though there is a 20% systematic uncertainty on our determination of T_C and T_F. We have also obtained samples colder than those presented in Fig. 4, for which the ^{7}Li thermal fraction is below our detectivity floor, indicating $T < 0.2 T_C \simeq 0.2 T_F$. Clearly a more sensitive thermal probe is required now to investigate this temperature domain. An elegant method relies on the measurement of thermalization rates with impurity atoms including Pauli blocking [18,19].

Because of the small scattering length, this ^{7}Li condensate has interesting properties. Time of flight images, performed after expansion times of 0–10 ms with $N_0 = 10^4$ condensed atoms, reveal that the condensate is one dimensional (1D). In contrast to condensates in the Thomas-Fermi (TF) regime, where the release of interaction energy
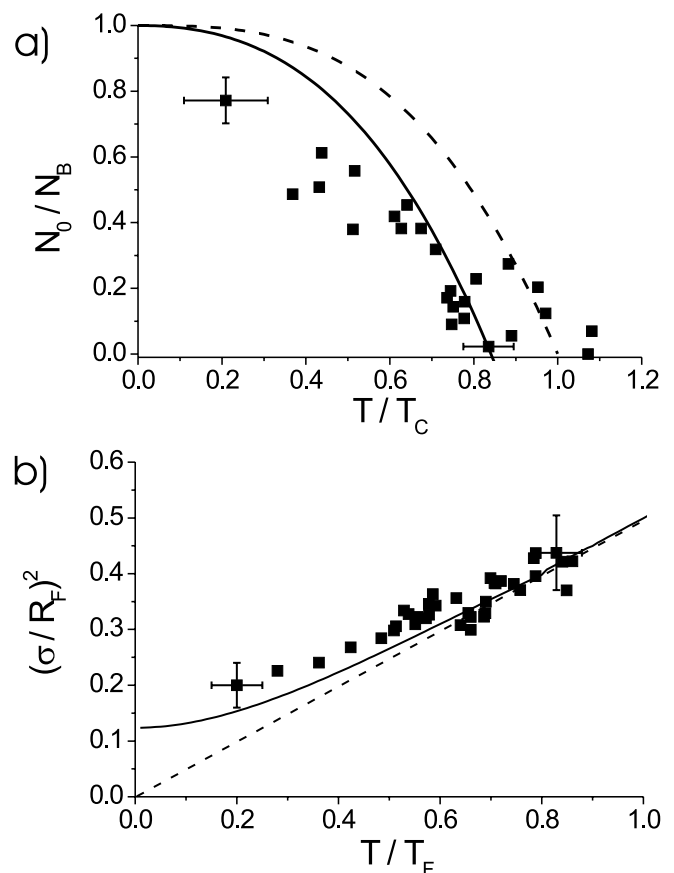

FIG. 4.   Temperature dependence of mixtures of quantum gases: (a) normalized BEC fraction as a function of T/T_C. Dashed line: theory in the thermodynamic limit. Solid line: theory including finite size and trap anisotropy [2]; (b) fermion cloud size: variance of Gaussian fit divided by the square of Fermi radius $R_F^2 = 2 k_B T_F / M \omega_{ax}^2$ as a function of T/T_F. Solid line: theory. Dashed line: Boltzmann gas.

leads to a fast increase in radial size, our measurements agree to better than 5% with the time development of the radial ground state wave function in the harmonic magnetic trap (Fig. 5). This behavior is expected when the chemical potential μ satisfies $\mu < \hbar\omega_{rad}$ [20]. Searching for the ground state energy of the many-body system with a Gaussian ansatz radially and TF shape axially [20], we find that the mean field interaction increases the size of the Gaussian by $\approx 3\%$. The calculated TF radius is 28 μm or 7 times the axial harmonic oscillator size and is in good agreement with the measured radius, 30 μm in Fig. 3. Thus with $\mu = 0.45\hbar\omega_{rad}$, the gas is described as an ideal gas radially but is in the TF regime axially. This 1D situation has also been realized recently in sodium condensates [21].

What are the limits of this BEC-Fermi gas cooling scheme? First, the $1/e$ condensate lifetime of about 3 s in this steep trap will limit the available BEC-Fermi gas interaction time. Second, the boson-fermion mean field interaction can induce a spatial phase separation [8] that prevents thermal contact between ^{7}Li and ^{6}Li. Using the method of [8] developed for $T = 0$, we expect, for the parameters of Fig. 3 (top), that the density of fermions is only very slightly modified by the presence of the condensate in accordance with our observations. Third, because of the superfluidity of the condensate, impurity atoms (such as ^{6}Li), which move through the BEC slower than the sound velocity v_c, are no longer scattered [9,22]. When the Fermi velocity v_F becomes smaller than v_c, cooling occurs only through collisions with the bosonic thermal cloud, thus slowing down drastically. With 10^4 condensed atoms, $v_c \simeq 0.9$ cm/s. The corresponding temperature where superfluid decoupling should occur is $\simeq 100$ nK, a factor of 14 lower than T_F.

In summary, we have produced a new mixture of Bose and Fermi quantum gases. Future work will explore the degeneracy limits of this mixture. Phase fluctuations of the 1D ^{7}Li condensate should also be detectable via density fluctuations in time of flight images, as recently reported in [23]. The transfer of the BEC into $|F = 2, m_F = 2\rangle$ with negative a should allow the production of bright solitons and of large unstable condensates where interesting and still unexplained dynamics has been recently observed [11,24]. Finally, the large effective attractive interaction between ^{6}Li $|F = 1/2, m_F = +1/2\rangle$ and $|F = 1/2, m_F = -1/2\rangle$ makes this atom an attractive candidate for searching for BCS pairing at lower temperatures [6].

  *Present address: LENS-INFM, Largo E. Fermi 2, Firenze 50125 Italy.
 [1] *Bose-Einstein Condensation in Atomic Gases,* Proceedings of the International School of Physics "Enrico Fermi," edited by M. Inguscio, S. Stringari, and C. E. Wieman (IOS Press, Amsterdam, 1999).
 [2] F. Dalfovo *et al.,* Rev. Mod. Phys. **71**, 463 (1999).
 [3] B. DeMarco and D. S. Jin, Science **285**, 1703 (1999).
 [4] F. Schreck *et al.,* Phys. Rev. A **64**, 011402R (2001).
 [5] A. G. Truscott *et al.,* Science **291**, 2570 (2001).
 [6] H. T. C. Stoof and M. Houbiers, in *Bose-Einstein Condensation in Atomic Gases* (Ref. [1]), p. 537; R. Micnas *et al.,* Rev. Mod. Phys. **62**, 113 (1990).
 [7] C. Ebner and D. O. Edwards, Phys. Rep. **2C**, 77 (1970).
 [8] K. Mølmer, Phys. Rev. Lett. **80**, 1804 (1998).
 [9] E. Timmermans and R. Côté, Phys. Rev. Lett. **80**, 3419 (1998).
[10] C. C. Bradley, C. A. Sackett, and R. G. Hulet, Phys. Rev. Lett. **78**, 985 (1997).
[11] J. M. Gerton *et al.,* Nature (London) **408**, 692 (2000).
[12] R. G. Hulet (private communication).
[13] M.-O. Mewes *et al.,* Phys. Rev. A **61**, 011403R (2000).
[14] D. A. Butts and D. S. Rokhsar, Phys. Rev. A **55**, 4346 (1997).
[15] In this measurement, we abruptly prepare an out of equilibrium ^{7}Li energy distribution in the trap using the microwave evaporation knife and measure the time needed to restore thermal equilibrium through the evolution of the axial size of the ^{7}Li and ^{6}Li clouds.
[16] T. Busch *et al.,* Europhys. Lett. **44**, 755 (1998); B. DeMarco and D. S. Jin, Phys. Rev. A **58**, 4267 (1998).
[17] F. A. Van Abeelen, B. J. Verhaar, and A. J. Moerdijk, Phys. Rev. A **55**, 4377 (1997).
[18] G. Ferrari, Phys. Rev. A **59**, R4125 (1999).
[19] B. DeMarco, S. B. Papp, and D. S. Jin, Phys. Rev. Lett. **86**, 5409 (2001).
[20] D. S. Petrov, G. V. Shlyapnikov, and J. T. M. Walraven, Phys. Rev. Lett. **85**, 3745 (2000).
[21] A. Görlitz *et al.,* cond-mat/0104549.
[22] A. P. Chikkatur *et al.,* Phys. Rev. Lett. **85**, 483 (2000).
[23] S. Dettmer *et al.,* cond-mat/0105525.
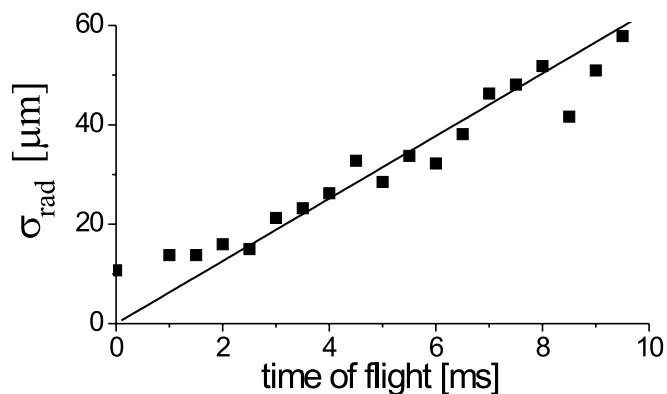[24] J. L. Roberts *et al.,* Phys. Rev. Lett. **86**, 4211 (2001).

FIG. 5.   Signature of 1D condensate. Radial size of expanding condensates with 10^4 atoms as a function of time of flight. The straight line is the expected behavior for the expansion of the ground state radial harmonic oscillator.