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Is Bose-Einstein condensation of atomic cesium possible?

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Abstract. – We investigate the dipole relaxation of a cesium atomic gas prepared in its lowest hyperfine level ($F = 3$) and confined in a magnetic trap. We measure a rate $\sim 4\times10^{-13}$ cm^{3}s^{-1}, for a field of 0.1 mT and a temperature 1 μK. This value is 2 orders of magnitude larger than for lighter alkalis. It puts strong constraints on the trapping mechanism which could lead to the Bose-Einstein condensation of cesium.

Since the recent observation of Bose-Einstein condensation (BEC) with gaseous samples of rubidium [1], lithium [2] and sodium [3], there have been a lot of efforts to extend this achievement to other atomic species. In particular, the BEC of cesium would be an important step in the improvement of the time and frequency standard based on the hyperfine splitting of its ground state. Here we show that inelastic collisions between the ultracold atoms make this aim very difficult to achieve, at least for a cesium gas confined in a magnetic trap.

The cesium atomic ground state ($6S_{1/2}$) is split into two hyperfine levels with angular momenta $F = 3$ and $F = 4$. For atoms prepared in the upper, doubly polarized state ($F = m_F = 4$) it has been shown that spin-dipole relaxation prevents reaching a regime of efficient evaporative cooling [4, 5], ruling out the achievement of BEC in the upper state [6].

In this article we focus on the study of a cesium gas prepared in the lower hyperfine level $F = 3$. The atoms are confined in a magnetic trap and prepared in the Zeeman substate with the highest energy, $F = -m_F = 3$. Indeed, because it is impossible to achieve a magnetic-field maximum in free space, a static magnetic trap is always centered around a local minimum. Atoms can only be trapped in a low-field seeking state which cannot be the lowest state of the atomic-level scheme.

Consequently, a magnetically trapped atomic sample is strictly speaking unstable with respect to two-body collisions. The magnetic dipole-dipole coupling may lead to a flip of the magnetic moment during a collision, with one or both atoms emerging in a lower Zeeman state and leaving the trap. For sodium and rubidium atoms prepared in the lower hyperfine manifold, the dipole relaxation does not constitute a limitation to the achievement of BEC. For a 0.1 mT magnetic field, the rates are predicted to be in the range of or below 10^{-15} cm^{3}s^{-1} [7], which corresponds to a 10 s lifetime for a condensate with a typical density 10^{14} cm^{-3}. In

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contrast, the data we present here indicate that the dipolar relaxation rate for cesium at 1 μK in the $F = -m_F = 3$ level is two orders of magnitude larger than this value. Dipole relaxation is therefore a major obstacle to cesium BEC in static magnetic traps.

The experimental setup is based on a double magneto-optical trap (MOT) system [4]. The atoms are captured in the upper MOT (10^8 atoms in 3 s), cooled with an optical molasses and then fall down to the lower cell located 70 cm below. They are recaptured in the lower MOT and cooled down to 6 μK using again a short molasses phase. The atoms are optically pumped into the state $F = -m_F = 3$ (efficiency $> 90\%$) by a 500 μs pulse of circularly polarized light, aligned with a magnetic field of 0.2 mT, and resonant with the transition $6S_{1/2}, F = 3 \leftrightarrow 6P_{3/2}, F' = 3$. An additional beam resonant with the transition $6S_{1/2}, F = 4 \leftrightarrow 6P_{3/2}, F' = 4$ depumps the atoms from the $F = 4$ sublevel.

We then switch on the magnetic trap, formed by three identical circular coils whose axes point towards $+x$, $-x$, and $+y$, respectively, where z denotes the vertical axis [4]. The resulting field configuration is equivalent to a Ioffe-Pritchard–type trap, with a non-zero local minimum of $|\mathbf{B}(\mathbf{r})|$. The leading terms in the field variations around the minimum ($\mathbf{r} = \mathbf{0}$) are $(b'x, B_0 + b''y^2/2, -b'z)$, with $b' = 1.1$ T/m, $b'' = 60$ T/m^2. B_0 is a bias field that can be adjusted by an extra pair of Helmholtz coils. The lifetime of the cloud due to the collisions with the residual background gas is $\tau \approx 200$ s.

The trapped cloud is adiabatically compressed by increasing the oscillation frequency in the x-z plane, $2\pi\,\nu_{x,z} = (3g\mu b'^{\,2}/(mB_0))^{1/2}$, where $g = 1/4$ is the Landé factor and μ is the Bohr magneton. For the compression B_0 is reduced within 5 s from $B_{0i} = 11$ mT down to an adjustable B_{0f} equal to a fraction of a mT. At this stage, taking for instance $B_{0f} = 0.12$ mT, the cigar-shaped atomic cloud contains about 5×10^7 atoms at a temperature of 120 μK and a peak density $7{\times}10^{10}$ cm^{-3}, with $\nu_{x,z} = 90$ Hz and $\nu_y = 6.9$ Hz.

We then prepare the atomic sample at an adjustable temperature using forced evaporation. This technique relies on the thermalization of the sample *via* elastic collisions, while the particles in the high energy tail of the phase-space distribution are being removed [8]. A radio frequency (RF) wave with a magnetic-field amplitude 3×10^{-6} T induces a cascade of adiabatic transitions from the substate $m_F = -3$ to the untrapped substate $m_F = 3$. This energy-selective transfer takes place on a surface $g\mu|\mathbf{B}(\mathbf{r})| = h\nu$ around the trap center. The RF frequency ν is ramped down linearly in 30 s, from 4 MHz to an adjustable final frequency.

The cloud is probed by absorption imaging. The current in the magnetic trap coils is switched off in less than 500 μs. The atoms are pumped into the $F = 4$ sublevel using a 200 μs light pulse resonant with the $6S_{1/2}, F = 3 \leftrightarrow 6P_{3/2}, F' = 3$ transition. The cloud is then briefly (80 μs) illuminated by a circularly polarized probe laser beam, propagating along the x-axis and resonant with the $6S_{1/2}, F = 4 \leftrightarrow 6P_{3/2}, F' = 5$ transition. The shadow produced by the cloud in this beam is imaged with a magnification 2.5 onto a CCD array (optical resolution 7 μm). The image is digitally processed to extract the column density of the cloud $\int n(x, y, z)\,\mathrm{d}x$, where $n(\mathbf{r})$ is the spatial density. This quantity is well fitted by a 2D Gaussian as expected for a thermal distribution in a harmonic trap. Assuming rotational symmetry around the y-axis, we then deduce the number of atoms N and the temperature T.

Once the atomic cloud is prepared at the desired temperature and the desired magnetic field at the center of the trap, we monitor the time evolution of N and T in order to deduce the value of the two-body rate coefficient. Each measurement is destructive, and we repeat the procedure for the same initial conditions and for various relaxation times.

We have performed two types of relaxation experiments. The first one is based on an RF shielding of the trap. In this case the RF remains *on* at a fixed value ν_{sh} during the relaxation period. Two competing criteria have to be fulfilled for the choice of ν_{sh}: i) It has to be small enough that any atom having undergone a spin-flip in a binary collision is ejected from the

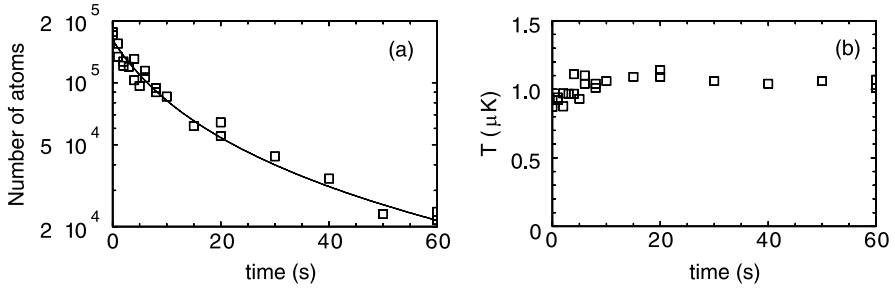

Fig. 1. – Time evolution of the number of atoms in log scale (a) and the temperature (b) in an RF-shielding relaxation experiment. The evolution of $N(t)$ is fitted by a two-body decay law.

trap. The gain of energy during a spin-flip collision is at least $g\mu B_0/2$ per atom. ii) $\nu_{\rm sh}$ has to be large enough that residual evaporation during the relaxation time plays little role. Therefore, the RF shielding method can be used to study the relaxation of clouds with $3k_{\rm B}T \ll \mu B_0/8$ ($T \ll 8\,\mu$K for $B_0 = 0.3$ mT).

A typical result of the RF shielding method is shown in fig. 1. It corresponds to $B_0 = 0.302$ mT, determined from the value of ν that completely empties the trap. The evolution of N (fig. 1a) exhibits a clear non-exponential decay that can be fitted quite accurately with a solution of

$$\frac{{\rm d}N}{{\rm d}t} = -G\,\bar{n}\,N - \frac{N}{\tau} \tag{1}$$

with $G = 2.3 \times 10^{-12}$ cm^{3}s^{-1} and $\tau = 220$ s. The quantity $\bar{n}$ is the average density, $\bar{n} = \int n^2(\mathbf{r})\,{\rm d}^3r/N \propto N$, where we have assumed a constant temperature.

At the beginning of the relaxation phase the temperature for this set of data is $0.9\,\mu$K (fig. 1b). We observe a slight *relaxation heating* up to $1.1\,\mu$K which can be understood simply. Inelastic processes occur preferentially in the center of the trap where the density is maximum. Atoms undergoing an inelastic collision have therefore a below-than-average potential energy and the elimination of these atoms leads to a heating of the cloud [8]. Actually, a simple analysis predicts a heating up to $1.5\,\mu$K. We do not completely understand this discrepancy, but a partial explanation may consist in the residual evaporation by the RF shield.

We have repeated the same experiment for various initial temperatures ranging from $0.25\,\mu$K to $2.6\,\mu$K. We fit $N(t)$ with (1) and $\tau = 220$ s, which minimizes the total χ^2 of all data sets. The variations of $G(B,T)$ with T (average temperature during the relaxation phase) are plotted in fig. 2a. In a double-log scale the points are distributed along a straight line, and a linear fit gives $G(0.302\,{\rm mT}, T) = 2.2 \times 10^{-12}\,T^{-0.78}$ cm^{3}s^{-1}, where T is in μK.

We have performed these RF shielding experiments with various magnetic fields B, varying between 0.12 mT and 0.69 mT, keeping an initial temperature close to 1 μK. To interpolate G to $T = 1\,\mu$K, we assume the same variation $G \propto T^{-0.78}$ as found for $B = 0.302$ mT. In fig. 2b the experimental results for $G(B, 1\,\mu{\rm K})$ are plotted. The points can be reproduced by a quadratic law (the best fit to a B^α-dependence gives $\alpha = 1.99 \pm 0.2$). All our data can therefore be summarized by the following law :

$$G(B,T) = (38 \pm 12) \times 10^{-12}\,B^2\,T^{-0.78}\ {\rm cm}^3{\rm s}^{-1} \quad , \tag{2}$$

where B is in mT and T in μK. The uncertainty of $\sim$30% is due to the determination of the number of atoms (20% error), the temperature (5% error) and the statistical error for the fits indicated by the error bars in fig. 2a.

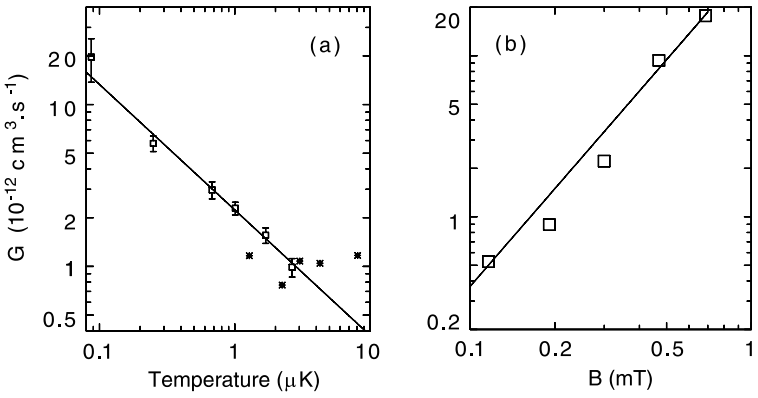

Fig. 2. – Variations of the two-body rate coefficient $G(B,T)$ with (a) the temperature T for fixed $B = 0.302$ mT, (b) the magnetic field B for fixed $T = 1\,\mu$K. In (a), the squares (stars) correspond to data obtained in a RF-shielding (pure heating) experiment.

In the second class of relaxation experiments no RF is applied during the relaxation phase. A typical result is given in fig. 3, recorded with $B_0 = 0.302$ mT. The decay of the number of atoms (fig. 3a) is well fitted with an exponential law, with a time constant equal to 170 seconds in the present case. We observe simultaneously a strong heating of the trapped atoms (fig. 3b), the temperature rising from 4.5 μK initially up to 15 μK after 200 seconds.

The modelling of this second class of data requires some hypotheses concerning the products of the inelastic collisions. In our trap, only atoms with $m_F = -3$ and $m_F = -2$ are trapped [9]. Therefore processes producing atoms in states $m_F = -1, 0, \ldots, 3$ are not dominant [10]. Otherwise we should observe a clear non-exponential decay because of the loss of these atoms. By contrast, as we see below, both of the two processes i) $(m_{F1}, m_{F2}) = (-3; -3) \rightarrow (-3; -2)$ and ii) $(-3; -3) \rightarrow (-2; -2)$ yield a G value in reasonable agreement with the preceeding determination.

The processes i) and ii) correspond to a pure heating of the trap sample with an energy released per collision of $g\mu B_0$ and $2g\mu B_0$, respectively. Consider first that only process i) is present. If we assume that the atomic sample essentially contains $m_F = -3$ atoms and if we neglect therefore collisions involving $m_F = -2$ atoms, we find that the evolution of the

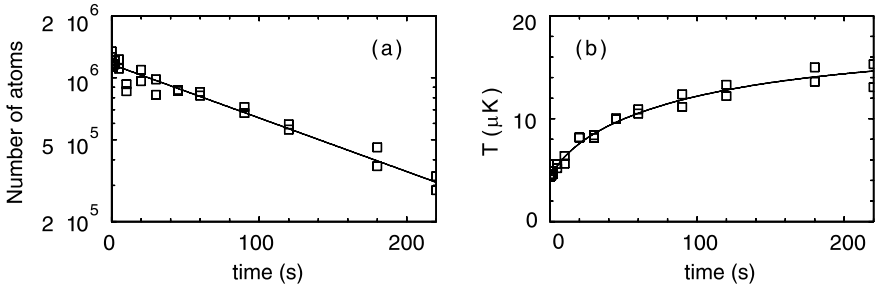

Fig. 3. – Evolution of (a) the number of atoms $N(t)$ and (b) the temperature $T(t)$ in a *pure-heating* relaxation experiment. The fit to $N(t)$ is exponential. The result is injected into the fit to $T(t)$ (see text), in order to deduce the two-body rate.

temperature is given by $\dot{T} = G\bar{n}(t)T_0$ with $3k_{\rm B}T_0 = g\mu B_0/2$. Using the exponential fit for the evolution of $N(t)$ (fig. 3a), we can solve this equation for $T(t)$ [11]. We determine the rate coefficient G by fitting the solution to the data in fig. 3b, yielding $G = 1.0 \times 10^{-12}$ cm^{3}s^{-1}. Now, if we assume that only process ii) is present, the same analysis leads to a G coefficient equal to half of this value.

Since we do not know the relative probabilities for the three processes, it is difficult to make a quantitative analysis of this second class of experiments. The analysis is even more difficult when one takes into account the $m_F = -2$ atoms which are present in the trap after some relaxation time. One should include in this case trap loss due to spin-exchange collisions: $(-2;-2) \rightarrow (-3;-1)$. Such collisions, which occur with higher probability than spin-flip collisions, should limit the number of $m_F = -2$ atoms to a small fraction of the number of $m_F = -3$ atoms [12].

For a consistency check we have plotted in fig. 2a, as a function of the initial temperature, the values of the G coefficients that we deduce from this second set of experiments using the simple analysis outlined above and assuming only i) is present. These values are in satisfactory agreement with the ones obtained with the more accurate shielding method.

We now discuss briefly our results in connection with the possible achievement of a cesium BEC. The measured rates ($> 10^{-13}$cm^{3}s^{-1}) are at least two orders of magnitude larger than for lighter alkali such as Na or Rb, for a similar temperature. As for cesium prepared in the upper hyperfine state $F = 4$ [4,13], this difference is probably associated with the large s-wave scattering length a for atoms prepared in the state $F = -m_F = 3$. In [14] we have shown that $|a| > 30$ nm by analysing evaporative cooling sequences. (For measurements of the elastic cross section for $T \geq 30\,\mu$K, see [15].) This is to be compared with 5.6 nm for ^{87}Rb and 2.9 nm for ^{23}Na in the lower hyperfine state. The large scattering length enhances the occupation probability at short relative distances for the low-energy collisional states of two Cs atoms and it favors any inelastic process occurring at such short distances. In addition, the short-range spin-spin coupling discussed in [16], arising as a second-order effect in the electronic spin-orbit coupling, may play a much more important role for Cs than for lighter alkalis.

We find that the dipole relaxation rate increases rapidly with B between 0.1 mT and 0.7 mT. As discussed in [17,18], this may be due to a Feshbach resonance close to $B = 0$. Note that the expected asymptotic behaviour for the dipole relaxation rate (Wigner law for $B \rightarrow 0$) is $G \propto \sqrt{B}$, where the long-range part (r^{-3}) of the spin-spin coupling is dominant [19], and $G \propto B^{5/2}$, where the short-range part is dominant.

This fast dependence with the magnetic field indicates that it should be possible to observe BEC with cesium atoms if one could operate the magnetic trap at a bias field much smaller than the present one. For instance, with a bias field $B_0 = 10^{-2}$ mT, the rate that we extrapolate from our result (2) is of the order of the one for doubly polarized Rb atoms [7]. Unfortunately, when we tried to run our magnetic trap with a reduced bias field, we observed a rapid decrease of the lifetime together with a density-independent heating (lifetime 5 s, heating $0.4\,\mu$K/s at $B_0 = 10^{-2}$ mT), preventing us from an efficient evaporative cooling. This limitation cannot be explained simply by Majorana spin flips at the center of the trap. For a spin-(1/2) particle with a kinetic energy $\sim \mu B_0$, the probability for a flip during a passage through $\mathbf{r} = \mathbf{0}$ is $e^{-\xi}$, where $\xi \propto B_0^{3/2}$ is equal to 1 for $B_0 \sim 10^{-4}$ mT. We therefore expect a trap lifetime > 10 s for $B_0 > 10^{-3}$ mT. The observed losses may be due to fluctuating stray magnetic fields and they might be overcome with an apparatus carefully shielded against external magnetic perturbations.

Another option to reach BEC with atomic cesium is to confine the atoms in the lowest level $m_F = 3$ of the $F = 3$ manifold by using a laser trap or a hybrid laser-magnetic trap, for example. In this case no binary inelastic process can occur, and the only limitations to

the achievement of BEC may lie in the 3-body recombination process, whose rate is currently unknown [20]. The sign of the scattering length for the $F = m_F = 3$ level [18] will then ultimately determine whether a stable condensate with an arbitrarily large number of cesium atoms can be formed.

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[6] Photo-association measurements have recently been performed: Fioretti A. *et al.*, *Phys. Rev. Lett.*, **80** (1998) 4402. They should ultimately allow for a determination of the scattering length for this state.

[7] See Boesten H., Moerdijk A. J. and Verhaar B. J., *Phys. Rev. A*, **54** (1996) R29, for theoretical predictions and a comparison with experimental results.

[8] See, *e.g.*, Luiten G. O. J., Reynolds M. W. and Walraven J. T. M., *Phys. Rev. A*, **53** (1996) 381; Ketterle W. and van Druten N. J., *Adv. At. Mol. Opt.*, **37** (1996) 181 and references therein.

[9] For $m_F = -1$ atoms, a calculation including gravity gives a trap depth lower than $g\mu B_0$.

[10] Due to the tensorial nature of the magnetic dipole-dipole coupling, only processes with $\Delta(m_{F1} + m_{F2}) \leq 2$ are possible to first order.

[11] In this simple qualitative model we assume G is temperature independent, although this is not strictly true, as indicated by the shielding results.

[12] By reducing after a variable relaxation time the magnetic-field gradient b' to a value such that $m_F = -2$ atoms fall out of the trap ($b' = 0.47$ T/m), we could crudely monitor the evolution of the number of atoms in $m_F = -2$. In the experimental conditions of fig. 3, the fraction of atoms in $m_F = 2$ reaches $\sim 20\%\pm7\%$ after 20 seconds relaxation time.

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[16] Julienne P., *J. Mol. Spectrosc.*, **56** (1975) 270; including this extra coupling, one can give a quantitative account for the $F = 4$ data of [4]: Leo P. J., Tiesinga E., Julienne P. S., Walter D. K., Kadlecek S. and T. G. Walker, *Phys. Rev. Lett.*, **81** (1998) 1389.

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[20] See, however, Boiron D. *et al.*, *Phys. Rev. A*, **57** (1998) R4106. In this experiment, cesium atoms have been confined in a laser trap at a peak density 10^{13} cm^{-3}, with a $1/e$ decay time ~ 0.3 s. This puts the upper bound 1.5×10^{-25} cm^{6}s^{-1} on the 3-body rate coefficient.