Bose-Einstein condensation of metastable helium: some experimental aspects

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We describe our recent realization of BEC using metastable helium. All detection is done with a
microchannel plate which detects the metastables or ions coming from the trapped atom cloud. This
discussion emphasizes some of the diagnostic experiments which were necessary to quantitatively
analyze our results.

I. INTRODUCTION

Since the announcement of the observation of Bose-Einstein condensation (BEC) in a rubidium vapor at the
12th ICOLS meeting in 1995[1], this fascinating state of
matter has occupied central stage in the field of atomic,
molecular and optical physics. The many new advances
reported at this meeting indicate that the field may con-
tinue to do so for some time to come. This paper concerns
one of these advances, the condensation of metastable hel-
im atoms (He*), and is intended as a supplement to the
recently published Ref. [2]. We shall not repeat the data
from that paper, but rather concentrate on some details
that were left out of Ref. [2] for lack of space.

Until recently BEC had been observed in 4 different
atomic species, H, Li, Na and Rb[3, 4, 5, 6], and the first
question to ask before embarking on the quest for BEC of
He* was whether a new atom was of interest. During the
1990s, several groups have been working on laser cooling
of He*, and of course one answer to the above question
is simply that the attainment of BEC is the best cooling
one can do, and many of the same justifications for laser
cooling apply to BEC. In addition, one might hope that a
new atomic species might allow one to observe new phe-
nomena, not accessible to the previously studied cases.
In this respect it seemed clear that the metastability of
the atoms might be very important. Simple, rapid and
efficient detection of the He* atoms is possible using elec-
tron multipliers such as microchannel plates (MCP) and
these detectors can also be used to observe ions resulting
from Penning ionizing collisions, either with residual
gas atoms or between the He* atoms themselves. Thus,
when BEC was observed in alkali gases, groups working
on laser cooling of He* naturally considered the feasibil-
ity necessary for evaporative cooling and BEC is
loading atoms from a MOT into a non-dissipative trap,
there was a danger that the density and more impor-
tantly the elastic collision rate would be too small to ef-
ciently cool by evaporation. In addition, it was known experimentally[3, 4, 5] and theoretically[6] that even
in the absence of resonant light, the rate constant for Pen-
ning ionization was on the order of $10^{-10}$ cm$^3$/s. Thus,
even if it were possible to begin evaporative cooling, such
a large inelastic collision rate is likely to prevent evapo-
rative cooling down to BEC.

On the other hand it was predicted[8, 9] that the elastic scattering length $a$ would be quite large for He*.
This result was very encouraging because it indicated
that despite the low densities achievable in a MOT, ther-
malizing collisions in a MOT-loaded magnetic trap could
be rapid enough to allow evaporative cooling.

Even more importantly, it was also known that, for
a spin polarized sample, the Penning ionization rate is
suppressed by spin conservation. He* has total angular
momentum one, therefore only one trapping state ex-
ists and magnetically trapped He* atoms are neces-
sarily 100% polarized. So one might hope to accumulate large
densities of He* in a magnetic trap. Experimentally, a
suppression of one order of magnitude had already been
demonstrated as early as 1972[15], this result was fol-
lowed up by more recent measurements[16, 17]. In the
mid 1990’s it was predicted that the degree of suppres-
sion could be as high as 5 orders of magnitude[18, 19],
which would easily permit long storage times at densi-
ties necessary for BEC. The theoretical predictions for
the scattering properties of He* motivated the serious
try to achieve BEC using a strategy analogous to
that used in the alkali gases.

II. EXPERIMENT

In our apparatus, a Zeeman cooled atomic beam loads a
MOT which, after an optical molasses cooling and an
optical pumping stage, loads a magnetic trap. The mag-
netic trap is of the cloverleaf design[20]. The only unusual
feature of the apparatus is an MCP placed 5 cm below
the trap center. A grid in front of the MCP allows one
to either attract or repel positive ions. The front face
of the MCP is at negative high voltage, and so electrons
are never detected. We typically trapped $3 \times 10^8$ atoms
in the MOT, and transferred approximately 50% to the

[http://atomoptic.iota.u-psud.fr/](http://atomoptic.iota.u-psud.fr/)
magnetic trap. The MOT temperature was typically of order 1 mK, while after molasses cooling, the atomic temperature reached 300 µK. After loading the magnetic trap, the atomic sample was compressed by lowering the magnetic field bias. During this process the temperature increased again to about 1 mK. Then, an RF-knife was applied and ramped down from 130 MHz to effect the forced evaporation.

The evolution of the temperature, phase space density and elastic collision rate during the evaporation ramp were all derived from measurements of the time of flight distribution of atoms to the MCP after the magnetic trap was turned off. Several examples are shown in Fig. 1. The change in gravitational energy of the atoms in falling 5 cm to the detector corresponds to 240 µK. For the initial temperature of the trapped atoms, this energy is negligible compared to the kinetic energy, and so the atoms expand nearly isotropically after release, and the collection efficiency of the detector corresponds roughly to its solid angle of 0.5%. In this situation, the time of flight distribution is peaked at a value corresponding to the flight time of an atom moving toward the detector with the most probable speed at that temperature. The signature for cooling is a shift of the arrival time toward later times as can be seen in Fig. 1. Unfortunately, as the atoms are evaporatively cooled, their number also diminishes and the detected signal drastically decreases. Indeed when the temperature is of order 100 µK, no signal is visible on the detector. As the temperature decreases further however, the atoms begin to fall down rather than fly away, and the collection efficiency of the detector increases dramatically. Near a temperature of 10 µK we observe a “revival” of the MCP signal, and at 1 µK, close to the BEC threshold, nearly all the atoms remaining in the trap reach the detector and we observe the characteristic structure of an expanding cloud below the BEC temperature: a broad peak whose width corresponds to the temperature and a narrow peak on top of it.

As is discussed in Ref. 2, a careful analysis of the narrow BEC peak reveals that its width increases as the 1/5 power of the number of atoms $N_0$ in the peak as predicted by the Gross-Pitaevski equation in the Thomas-Fermi approximation. Upon closer examination however, the results were puzzling. First, it was surprising that we detected the atoms at 1 µK at all. A magnetic field gradient as small as 30 mG/cm is enough to deviate the atomic trajectory so as to miss the MCP. We were virtually certain that residual field gradients larger than this were present in the apparatus. Secondly, the study of the expansion of the gas depends on being able to turn the trap off suddenly compared to the inverse of the oscillation frequencies in the trap (50 and 1300 Hz). Here again we were certain from magnetic field measurements that effects such as eddy currents in the reentrant flanges holding the magnetic trap coils, limited our field turn-off time to about 1 ms. Thirdly, we could estimate the number of atoms in the cloud at or near the critical temperature and compare it with the expected number in the ideal gas limit. The predicted number is given by [23]:

$$N_c = 1.202 \left( \frac{kT_c}{\hbar \omega} \right)^3.$$  \hspace{1cm} (1)

Here $\omega$ denotes the geometric mean of the trap oscillation frequencies. Our calibration of the detector indicated a number of atoms smaller than this by an order of magnitude. Finally a quantitative analysis of the $N_0^{1/5}$ dependence, resulted in an estimate of the scattering length $a$ of order 100 nm. Such a large value of the scattering length seemed to be ruled out by the fact that the condensate had a lifetime of a few s. One expects the 3 body loss rate to scale as the fourth power of $a$, and therefore 3 body losses would have caused the BEC to decay in much less than 1s.

A clue to resolving these difficulties came from earlier, in situ measurements of the magnetic fields in our apparatus when the trap was turned off. In Fig. 3 we show the results of such a measurement. We began with atoms in a magnetic trap at 1 mK. While monitoring the MCP signal, we directed a 10 mW/cm² laser pulse of 20 µs duration at the cloud at a time $t$ after the magnetic field turnoff. When the laser, which propagated parallel to the bias field, was resonant with the atoms, including the Zeeman shift due to the trapping fields, the atoms scattered the laser light and were pushed from the path.
The height of the peak generated by the gradient and the arrival time shifts with other peak occurs earlier, corresponding to atoms accelerated by the applied gradient. The location and height of this peak approximately 100 ms after the field turnoff, as occurs without observing the time of flight spectrum. The results are shown in Fig. 3. The gradient was turned on about 100 ms from the turnoff. The figure shows two peaks, one arriving at approximately 100 ms after the field turnoff, as occurs without an applied gradient. The location and height of this peak does not depend on the magnitude of the gradient. The other peak occurs earlier, corresponding to atoms accelerated by the gradient and the arrival time shifts with the magnitude of the gradient. The height of the peak can be varied by varying the horizontal components of the gradient. The figure shows the largest early peak we were able to produce. These data show that indeed a fraction of the atoms makes the flight to the detector in the $m = 0$ state and that at least 7 times more atoms are in a field sensitive state after the trap turnoff. The applied gradient was produced by a coil above the trap and thus the atoms which are accelerated are weak field seekers ($m = +1$). It is also possible that some atoms are in the strong field seeking state ($m = -1$), but since they are accelerated upwards, they have little chance to reach the MCP.

To get an estimate of the number of atoms in the magnetic trap we can use an analysis similar to that which leads to Eq. 1 leading to the number $N_{\text{th}}$ of atoms in the thermal cloud below the critical temperature. By fitting the wings of the time of flight spectra, we are able to determine the temperature $T$ of the atomic cloud, and to infer $N_{\text{th}}$. As discussed in Ref. [21], and experimentally demonstrated in Refs. [24, 25], this number should be given by: $N_{\text{th}} = 1.202 (kT/\hbar \omega)^3$. This relation gives an absolute thermodynamic measurement of the number of atoms. It is higher by a factor $f = 8 \pm 4$ than the value we derive from the calibration of the MCP. Taking this correction into account, the largest condensate we have observed contained about $10^5$ atoms, and the number of atoms present at the critical temperature is a few times $10^5$.

The magnetic field measurements also help to explain why the analysis of the expansion of the trapped atoms after release works so well. Because of the fast reversal, the atoms which make transitions to the $m = 0$ state are indeed released extremely rapidly. A careful analysis of the expansion may require taking into account the behavior of the weak field seeking atoms observed in Fig. 3. Here we assume that all atoms expand freely independent of their internal state. In fact the atoms...
in this state are presumably trapped during the decay of the eddy currents, but since in a cloverleaf trap, the confinement rapidly decreases with increasing bias, it is probably a good approximation to treat the atoms as free on the scale of 1 ms.

An analysis of the mean field expansion of the cloud, using the corrected number of atoms leads to a value of the scattering length, $a = 20 \pm 10$ nm. This result is consistent with our elastic rate constant measurements at 1 mK\(^{20}\), as well as with the observations of Ref. \[^{23}\].

We have also observed the ions produced by the trapped condensate, by negatively biasing a grid above the MCP. An example of the ion detection rate as a function of time is shown in Fig. 4 of Ref. \[^{2}\]. These ions are due to Penning ionization of residual gases, to two body collisions within the condensate, or possibly other, more complicated processes. We observe a factor of 5 more ions from the condensate than from a thermal cloud at 1 µK, and we attribute this increase to the larger density in the condensate. The lifetime of the condensate, estimated by observing the ion rate is on the order of a few seconds. This is true both with and without an RF-knife to evacuate hot atoms\[^{23, 27}\], although the lifetime is slightly longer with the knife present. The density of the condensate, deduced from its vertical size measurement and its known aspect ratio, is of order $10^{13}$ cm\(^{-3}\), so from the lifetime we can place an upper limit of $10^{-13}$ cm\(^3\)s\(^{-1}\) on the relaxation induced Penning ionization rate constant, as well as an upper limit of $10^{-26}$ cm\(^{-6}\)s\(^{-1}\) on any three-body loss process.

The achievement of BEC in He\(^*\) together with a MCP detector, offers many new possibilities for the investigation of BECs. Ion detection allows continuous “non-destructive” monitoring of the trapped condensate. We hope to be able to study the formation kinetics of the condensate using the ion signal. Our ability to count individual He\(^*\) atoms falling out of the trap should allow us to perform accurate comparisons of correlation functions\[^{22}\] for a thermal beam of ultracold atoms\[^{28}\] and for an atom laser, realizing the quantum atom optics counterpart of one of the fundamental experiments of quantum optics.

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\[1\] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, E. A. Cornell, Proceedings of the 12 International Conference on Laser Spectroscopy, Capri, June 1995, M. Inguscio, M. Allegrini and A. Sasso Eds., (World Scientific, Singapore, 1996).

\[2\] A. Robert, O. Sirjean, A. Browaeys, J. Poupard, S. Nowak, D. Boiron, C. I. Westbrook, A. Aspect, Science, 292, 463 (2001), published online 22 March 2001, 10.1126/science.1060622.

\[3\] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, E. A. Cornell, Science 269, 198 (1995).

\[4\] K. B. Davis \textit{et al}., Phys. Rev. Lett. 75, 3969 (1995).

\[5\] C. C. Bradley, C. A. Sackett, J. J. Tollet, R. G. Hulet, Phys. Rev. Lett. 75, 1687 (1995).

\[6\] D. G. Fried \textit{et al}., Phys. Rev. Lett. 81, 3811 (1998).

\[7\] W. Vassen, OSA TOPS on Ultracold Atoms and BEC 7, 20, K. Burnett, Ed. (Optical Society of America, Washington, DC, 1996).

\[8\] F. Bardou, O. Emile, J. M. Courty, C. I. Westbrook, and A. Aspect, Europhys. Lett. 20, 681 (1992).

\[9\] H. C. Mastwijk, J. W. Thomsen, P. van der Straten, and A. Niehaus, Phys. Rev. Lett. 80, 5516 (1998).

\[10\] P. J. J. Tol, N. Herschbach, E. A. Hessels, W. Hogervorst, and W. Vassen, Phys. Rev. A 60, 761 (1999).

\[11\] M. Kumakura and N. Morita, Phys. Rev. Lett. 82, 2848 (1999).

\[12\] A. Browaeys, J. Poupard, A. Robert, S. Nowak, W. Rooijakkers, E. Arimondo, L. Marcassa, D. Boiron, C. I. Westbrook, and A. Aspect, Eur. Phys. J. D 8, 199 (2000).

\[13\] F. Pereira Dos Santos, F. Perales, J. Léonard, A. Sinatra, Junmin Wang, F. S. Pavone, E. Rasel, C. S. Unnikrishnan, and M. Leduc, Eur. Phys. J. D 14, 15 (2001).

\[14\] V. Venturi and I. Whittingham, Phys. Rev. A, 61, 060703 (2000).

\[15\] J. C. Hill, L. L. Hatfield, N. D. Stockwell, and G. K. Walters, Phys. Rev. A 5, 189 (1972).

\[16\] N. Herschbach, P. J. J. Tol, W. Hogervorst, and W. Vassen, Phys. Rev. A 61, 050702(R) (2000).

\[17\] S. Nowak, A. Browaeys, J. Poupard, A. Robert, D. Boiron, C. I. Westbrook, and A. Aspect, Appl. Phys. B 70, 455 (2000).

\[18\] P. O. Fedichev, M. W. Reynolds, U. M. Rahmanov, G. V. Shlyapnikov, Phys. Rev. A 53, 1447 (1996); G. V. Shlyapnikov, T. M. Walraven, U. M. Rahmanov, M. W. Reynolds, Phys. Rev. Lett. 73, 3247 (1994).

\[19\] V. Venturi, I. B. Whittingham, P. J. Leo, G. Peach, Phys. Rev. A 60, 4635 (1999), P. Leo, V. Venturi, I. Whittingham, J. Babb, preprint arXiv:physics/0011072.

\[20\] M. O. Mewes, M. R. Andrews, N. J. van Druten, D. M. Kurn, D. S. Durfee, and W. Ketterle, Phys. Rev. Lett. 77, 416 (1996).

\[21\] F. Dafolvo, S. Giorgini, L. P. Pitaevskii, Rev. Mod. Phys. 71, 463 (1999), and references therein.

\[22\] P. Fedichev, M. Reynolds, G. Shlyapnikov, Phys. Rev. Lett., 77, 2921 (1996).

\[23\] L. V. Hau et al., Phys. Rev. A 58, R54 (1998).

\[24\] J. R. Ensher, D. S. Jin, M. R. Matthews, C. E. Wieman, E. A. Cornell, Phys. Rev. Lett. 77, 4984 (1996).

\[25\] V. Venturi, A. Browaeys, A. Robert, O. Sirjean, J. Poupard S. Nowak, D. Boiron, C.I. Westbrook, A. Aspect, Phys. Rev. A 64, 034703 (2001).

\[26\] F. Pereira dos Santos, J. Leonard, J. Wang, C. Barrelet, F. Perales, E. Rasel, C.S. Unnikrishman, M. Leduc, C.
Cohen-Tannoudji, *Phys. Rev. Lett.* **86**, 3459 (2001).
[27] E. A. Burt *et al.*, *Phys. Rev. Lett.* **79**, 337 (1997).

[28] Y. Yasuda, F. Shimizu, *Phys. Rev. Lett.* **77**, 3090 (1996).