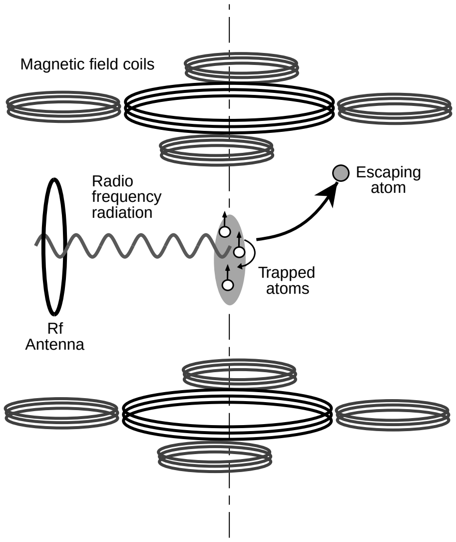
Progress in year 1996

1. *Cloverleaf magnetic trap*

The magnetic traps used in 1995 in BEC experiments had major disadvantages or limitations: The time-dependent rotating field of the TOP trap [1], the inflexibility of a permanent magnet trap [2], the complications of having two condensates in the optically plugged trap [3], or the restrictions of a cryogenic environment necessary for superconducting coils [4, 5]. In March 1996, we achieved BEC in a novel "cloverleaf" magnetic trap [6] which overcame those limitations. This trap used dc electromagnets, had excellent optical access, and allowed independent control over the axial and radial confinement. It is a variant of the Ioffe-Pritchard trap: the coils providing the radial gradient surround the two axial coils (the so-called pinch coils) in the form of a cloverleaf. If a Ioffe-Pritchard trap is operated at very low bias field it provides tighter confinement than the TOP trap [6].



Experimental setup for cooling atoms to Bose-Einstein condensation. Sodium atoms are trapped in a cloverleaf magnetic trap. Evaporative cooling is controlled by radio-frequency radiation from an antenna. The rf selectively flips the spins of the most energetic atoms. The remaining atoms re-thermalize (at a lower temperature) by collisions among themselves. Evaporative cooling is forced by lowering the rf frequency.

In the last few years, many efforts went into the development of novel atom traps. It is somewhat surprising that, in the end, the most suitable magnetic trap for BEC turned out to be an optimization of the configuration suggested already in 1983 [7], which was used in the late 80's for trapping sodium [8] and atomic hydrogen [4, 5].

2. *Study of the phase transition*

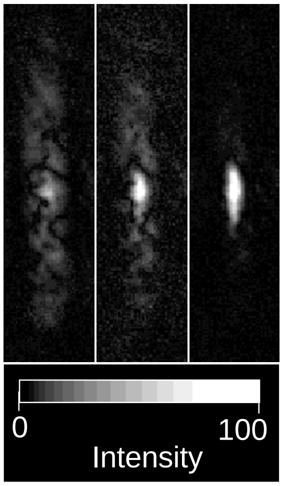
We studied several equilibrium properties of Bose-Einstein condensates. By evaluating time-of-flight images, the total number of atoms, the condensed fraction N_0/N, the internal energy of the condensate, and the temperature T were determined. Below the critical temperature T_c, the condensate fraction was predicted to vary as $N_0/N=1-(T/T_c)^3$, in agreement with our results. Furthermore, we could verify that the internal energy of a Bose condensate scales with the number of condensed atoms as $N_0^{2/5}$ [6].

3. Non-destructive imaging of a Bose condensate

The first BEC experiments were done by switching off the trap and imaging an expanding condensate. This technique is necessarily destructive and probes the condensation phenomenon only in momentum space. However, in an inhomogeneous potential, e.g. in atom traps, the condensate and the normal fraction of a Bose gas are spatially separated [9]. Using dispersive imaging, we observed the spatially localized condensate [10].

Dispersive imaging collects the elastically scattered photons, in contrast to absorption imaging which maps out the spatial distribution of absorbed photons. The scattered photons can be separated from the incident light in the Fourier transform plane of the imaging system by spatial filtering.

The figure shows dark ground images taken around and below the BEC phase transition. It shows the growth of the condensate fraction inside the saturated Bose gas. Dispersive imaging is non-dissipative and does not heat up the condensate. More recently, we took over twenty images of the same condensate. This real-time observation of dynamical processes played an important role in many subsequent studies.

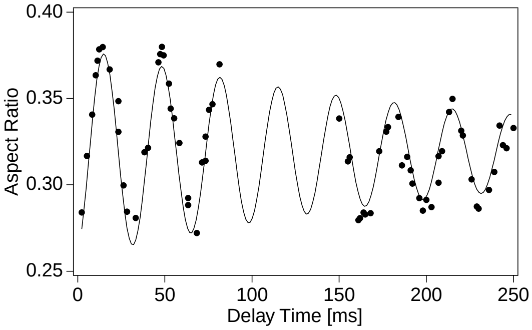


First direct observation of a Bose condensate of magnetically trapped atoms. The figures show clouds with a condensate fraction that is increasing from close to 0% (left) to almost 100 % (right).

4. Study of collective excitations

Bose condensates are predicted to show superfluidity. As a first step towards the study of dynamic properties of a Bose condensate, we investigated the low energy collective excitations [11], contemporaneous with a similar study undertaken at Boulder [12]. Collective modes were excited by introducing a small time-dependent modulation in the trapping potential for a short period of time. When the perturbation was removed, the condensate was allowed to oscillate for a chosen time and was then released into ballistic expansion. The oscillatory behavior of the condensate was thus detected in velocity-space as shape oscillations in time-of-flight pictures (see figure).

The observed frequencies were in excellent agreement with the predictions of mean field theory, being one of the most accurate tests of this theory [11]. The nature of the damping is not yet fully understood, and requires more theoretical and experimental work.

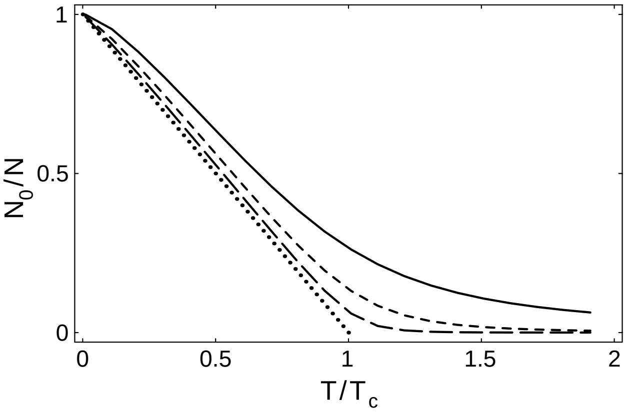


Collective oscillations of a Bose condensate. Shown is the aspect ratio of the ballistically expanding cloud versus evolution time in the trap. These oscillations correspond to standing sound waves.

5. Bose-Einstein condensation of a finite number of particles trapped in one or three dimensions

Bose-Einstein condensation (BEC) of an ideal gas was theoretically investigated for a finite number of particles [13]. This was done by considering the discrete quantum states in a harmonic oscillator potential.

In three dimensions, we found a transition temperature which is lower than in the thermodynamic limit and calculated the corrections. Lowering the dimension increases the transition temperature and is therefore favorable for BEC. This is in contrast to the standard result obtained in the thermodynamic limit which states that BEC is not possible in, e.g., a one-dimensional (1D) harmonic potential. As a result, 1D atom traps, such as radially tightly confining magnetic traps or optical dipole traps, are promising for studying BEC.



The condensate fraction for a finite number N of atoms in a one-dimensional harmonic potential versus temperature. Plots are shown for N=100 (solid line), 10^4, 10^8 and infinite (dotted).

1. M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell, Science **269**, 198 (1995).
2. C.C. Bradley, C.A. Sackett, J.J. Tollet, and R.G. Hulet, Phys. Rev. Lett. **75**, 1687 (1995).
3. K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle, Phys. Rev. Lett. **75**, 3969 (1995).

4. H. Hess, G.P. Kochanski, J.M. Doyle, N. Masuhara, D. Kleppner, and T.J. Greytak, Phys. Rev. Lett. **59**, 672 (1987).
5. R. van Roijen, J.J. Berkhout, S. Jaakkola, and J.T.M. Walraven, Phys. Rev. Lett. **61**, 931 (1988).
6. 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).
7. D.E. Pritchard, Phys. Rev. Lett. **51**, 1336 (1983).
8. V.S. Bagnato, G.P. Lafyatis, A.G. Martin, E.L. Raab, R.N. Ahmad-Bitar, and D.E. Pritchard, Phys. Rev. Lett. **58**, 2194 (1987).
9. K. Huang, *Statistical Mechanics*, second edition (Wiley, New York, 1987).
10. M.R. Andrews, M.-O. Mewes, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle, Science **273**, 84 (1996).
11. M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.M. Kurn, D.S. Durfee, C.G. Townsend, and W. Ketterle, Phys. Rev. Lett. **77**, 988 (1996).
12. D.S. Jin, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell, Phys. Rev. Lett. **77**, 420 (1996).
13. W. Ketterle and N.J. van Druten, Phys. Rev. A **54**, 656 (1996).