Atom Laser

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An atom laser is a device which generates an intense coherent beam of atoms through a stimulated process. It does for atoms what an optical laser does for light. The atom laser emits coherent matter waves whereas the optical laser emits coherent electromagnetic waves. Coherence means, for instance, that atom laser beams can interfere with each other.
(see de Broglie wavelength, laser)

Laser light is created by stimulated emission of photons, a light amplification process. Similarly, an atom laser beam is created by stimulated amplification of matter waves. The conservation of the number of atoms is not in conflict with matter wave amplification: The atom laser takes atoms out of a reservoir and transforms them into a coherent matter wave similar to the optical laser which converts energy into coherent electromagnetic radiation (but, in contrast, the number of photons needs not to be conserved).

The condition of high intensity means many particles per mode or quantum state. A thermal atomic beam has a population per mode of only 10^{-12} compared to >>1 for an atom laser. The realization of an atom laser therefore required methods to largely enhance the mode occupation - this is done by cooling to (sub-)microkelvin temperatures.

In the case of an ideal atom laser, the output beam should be monochromatic, directional, and have a well-defined phase and intensity. For atoms, monochromatic means that their velocity spread is extremely small. Such beams propagate with minimum spreading, and can be focused by atom lenses to a small spot size. The minimum spreading and the minimum spot size are limited by Heisenberg's uncertainty relation in the same way as the propagation of a single mode (optical) laser beam is diffraction limited. The analogy between light and matter waves is exploited in the field of atom optics.
(see atom optics)

The different nature of atoms and photons implies different properties of light and atom beams. Unlike light, an atomic beam cannot travel far through air. It scatters off air molecules in less than a micrometer. Vacuum is required for all atom laser experiments. Also, slow atoms are strongly affected by gravity. Furthermore, a dense atom beam will show spreading in excess of the Heisenberg uncertainty limit due to the interactions between the atoms.

The elements of an atom laser. A laser requires a cavity (resonator), an active medium, and an output coupler (see Table 1). Various "cavities" for atoms have been realized, the most important ones are magnetic traps (which use the force of an inhomogeneous magnetic field on

the atomic magnetic dipole moment) and optical dipole traps (which uses the force exerted on atoms by focused laser beams). Confinement of atoms between two atom mirrors has been suggested and is analogous to a Fabry-Perot type cavity for light. Even single mirror cavities are possible, where atoms perform multiple bounces off a mirror in the vertical direction and return due to gravity (atomic trampoline).
(see particle traps)

The active medium is a reservoir of atoms which are transferred to one state of the confining potential - the "lasing" mode. The reservoir can be atoms confined in other quantum states of the atom cavity or an ultraslow atomic beam. The atoms are transferred to the lasing mode either by collisions or by optical pumping. The transfer of atoms is only efficient for an ultracold sample which is prepared by laser cooling or evaporative cooling. This ensures that the atoms in the reservoir occupy only a certain range of quantum states which can be efficiently coupled to the lasing mode.
(see laser cooling)

The purpose of the output coupler is to extract atoms out of the cavity, thus generating a (pulsed or continuous) beam of coherent atoms. A simple way to accomplish this is to switch off the atom trap and release the atoms. This is analogous to cavity dumping for an optical laser and extracts all the stored atoms into a single pulse. A more controlled way to extract the atoms requires a coupling mechanism between confined quantum states and a propagating mode. Such a "beam splitter" for atoms was realized using the Stern-Gerlach effect. A short rf pulse rotated the spin by a variable angle, and the inhomogeneous magnetic trapping field separated the atoms into trapped and outcoupled components (Fig. 1). By using a series of rf pulses, a sequence of coherent atom pulses could be formed (Fig. 2). Other output coupling schemes have been suggested: optical transitions which eject atoms from the cavity due to the absorbed photon recoil, and tunneling through thin barriers of light.

The gain process in an atom laser. An atom laser is only possible for bosonic atoms. The accumulation of atoms in a single quantum state is based on Bose-Einstein statistics. Two different mechanisms have been discussed which may provide gain in an atom laser: elastic collisions and spontaneous emission of photons. The case of elastic collisions is discussed first.

This is the case which is closely related to Bose-Einstein condensation (BEC). When a gas of bosonic particles is cooled down, it forms a Bose condensate characterized by a macroscopic occupation of the ground state of the system. This process happens suddenly at the BEC transition temperature. The atoms in a Bose condensate are coherent to first and higher order. An atom laser based on Bose-Einstein condensation operates in thermal equilibrium. "Atom lasing" is achieved simply by cooling down the gas. Below a certain temperature, nature maximizes entropy by generating a Bose condensate. For photons, the situation is very different: Lowering the temperature T of a black-body cavity reduces the energy density proportional to T^4 (Stefan-Boltzmann law), i.e. at very low temperatures the cavity is empty. That's how entropy is maximized when the number of particles is not conserved.

It is instructive to look more closely at the stimulated amplification process which takes place when a Bose condensate forms. In a normal gas, atoms scatter among a myriad of possible quantum states. But when the critical temperature for Bose-Einstein condensation is reached, they scatter predominantly into the lowest energy state of the system. This abrupt process is closely analogous to the threshold for operating an optical laser. The presence of a Bose-Einstein condensate causes stimulated scattering into the ground state. More precisely, the presence of a condensate with N_0 atoms enhances the probability that an atom will be scattered into the condensate by a factor of N_0+1.

In an atom laser, the "excitation" of the "active medium" can be done by evaporative cooling - the evaporation process creates a cloud which is not in thermal equilibrium and relaxes towards colder temperatures. This results in growth of the condensate. After equilibration, the gain process halts and the condensate fraction remains constant until further cooling is applied. In thermal equilibrium, there is still stimulated scattering of atoms into the condensate. However, this process is in dynamic equilibrium with collisions which knock atoms out of the condensate ("detailed balance").

An atom laser was realized by extracting a beam of atoms from a Bose condensate (see above) and explicitly demonstrating its coherence. The proof of the coherence was obtained by observing a high contrast interference pattern when two Bose condensates overlapped. This pattern could be directly photographed (Fig. 3). It had a period of 15 micrometer, a gigantic length for matter waves. (Room temperature atoms have a matter wavelength of 0.05 nm, 300,000 times smaller).
(see Bose-Einstein statistics)

An atom laser based on BEC is a special case of macroscopic occupation of a quantum state. In this case, the atoms accumulate in the ground state and are in thermal equilibrium. More generally, atom lasers can operate in higher order modes and also as a driven system which is not in thermal equilibrium (this is the situation in an optical laser). The lasing mode is distinguished by preferential population of atoms and/or minimum loss. It has been suggested that this can be realized by optical pumping. In this case, atoms in the reservoir are optically excited, and when they decay by spontaneous emission, they can reach final momentum states which differ from the initial momentum by the photon recoil. If one state within this range has a macroscopic population, then the rate of spontaneous emission into this final state is enhanced, and there is an amplification process similar to the one described above for elastic collisions. The case of optically excited atoms shows very clearly the symmetry between the optical laser and the atom laser: The rate of emission to a final state $|m,\nu\rangle$, where m denotes the state of the atom inside the cavity, and ν the mode of the photon field, is proportional to $(N_m+1)(n_\nu+1)$, where N_m is the number of atoms in the level m of the cavity, and n_ν the number of photons in mode ν. The first factor is the bosonic stimulation by atoms which is responsible for the amplification process in the atom laser, and the second describes the amplification process in the optical laser.

Potential use of an atom laser. Although a basic atom laser has now been demonstrated, major improvements are necessary before it can be used for applications, especially in terms of

increased output “power” and reduced overall complexity. The atom laser provides ultimate control over the position and motion of atoms at the quantum level, and might find use where such precise control is necessary, e.g. for precision measurements of fundamental constants, tests of fundamental symmetries, atom optics (in particular atom interferometry and atom holography) and precise deposition of atoms. Since the matter wavelength of atoms can be extremely short (it decreases inversely proportional to the atomic velocity), the ultimate limit to the spatial resolution is not the matter wavelength, but the size of the atom.
(see atom optics)

References

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Figure captions

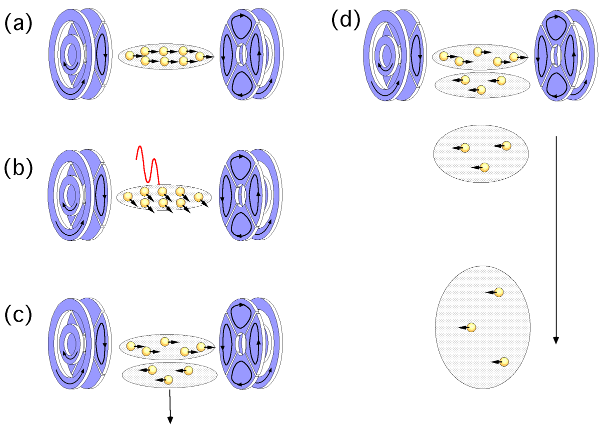

Figure 1: The rf output coupler for an atom laser. Figure (a) shows a Bose condensate trapped in a magnetic trap. All the atoms have their (electron) spin up, i.e. parallel to the magnetic field. (b) A short pulse of rf radiation tilts the spins of the atoms. (c) Quantum-mechanically, a tilted spin is a superposition of spin up and down. Since the spin-down component experiences a repulsive magnetic force, the cloud is split into a trapped cloud and an out-coupled cloud. (d) Several output pulses can be extracted, which spread out and are accelerated by gravity.

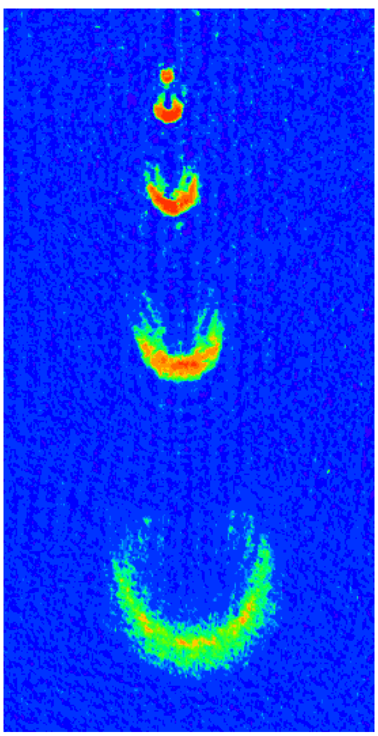

Figure 2: A pulsed atom laser in operation. The picture (field of view 2.5 mm x 5.0 mm) shows pulses of coherent sodium atoms coupled out from a Bose-Einstein condensate confined in a magnetic trap. Every five milliseconds, a short rf pulse rotated the magnetic moment of the trapped atoms, transferring a fraction of these atoms into a quantum state which is no longer confined. These atoms were accelerated downward by gravity and spread out. The atom pulses

were observed by illuminating them with resonant laser light and imaging their shadows which were caused by absorption of the light. Each of them contained between 10^5 and 10^6 atoms.

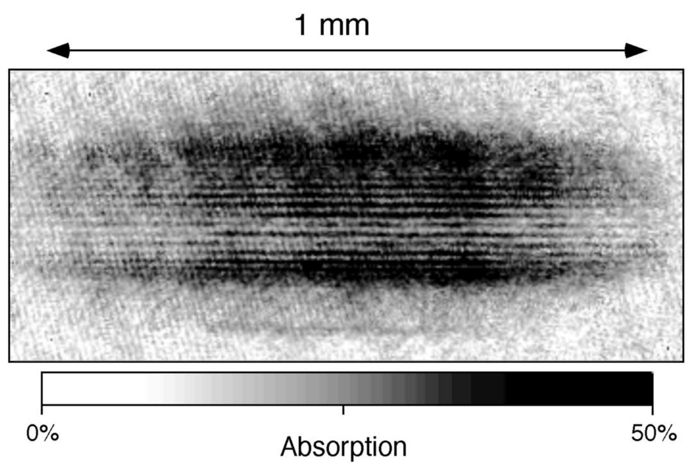

Figure 3: Interference of two Bose-Einstein condensates, demonstrating their coherence. Two condensates were created by cooling down a gas of sodium atoms in a double well potential. After releasing the condensates from the trap, they fell down, spread out ballistically and eventually overlapped. In the overlap region, a high contrast interference pattern with a fringe period of 15 micrometer was observed. The field of view was 1.1 mm by 0.5 mm.

Tables

Table 1: Analogies between an atom laser (based on evaporative cooling) and the optical laser

Atom Laser	**Optical Laser**
Atoms	Photons
Matter waves	Electromagnetic waves
Atom trap	Laser cavity
Atoms in the Bose condensate	Photons in the lasing mode
Thermal atoms	Gain medium
Evaporative cooling	Excitation of the gain medium
Stimulated scattering of atoms	Stimulated emission of photons
Critical temperature for Bose-Einstein condensation	Laser threshold