Atom lasers, Harvey Kaplan

In a typical photon laser, light is emitted as a coherent beam of photons. In the classical view of light, this corresponds with the superposition of the E&M fields of the light when they are all in phase. When considering the quantum nature of light, matter has a particle/wave duality that is expressed with the deBroglie wavelength formula that links the mass and momentum of a particle to its deBroglie wavelength, . With the realization of the Bose-Einstein condensate (BEC) state of matter it was demonstrated that it was possible to condense a collection of bosons, each of which reside in the ground state of the system. This was achieved with atoms which are composed of fermions, but the net spin of the entire atom as a whole can be of integer spin and therefore be a net boson.

In the BEC state, the collection of bosons, all in the same state, can be described by a single wave function. This becomes plausible by considering ([7] eq.11.53) (which assumes no interaction between atoms) and noting that the de Broglie wavelength of the atoms increase as the temperature drops. With the wave aspect of the atoms dominant in this state of matter, one can question the parallel between physical E&M waves and the more abstract probability wave which describes the atoms and ask whether the atoms can be organized into a laser. With an atom laser an important question to ask is whether a high enough level of coherence will allow for clear demonstrations of dispersion, diffraction, and reflection. Unlike photons in a photon laser, the atoms in an atom laser interact with each other. These atoms also interact with the remaining BEC and the trapping potential which will be described later. These interactions contribute to divergence of the atom beam which is one example of properties of atom lasers that are not seen in photon lasers.

Making a BEC requires making the collection of subject atoms very cold which presents challenges. In particular, measures need to be taken so the gas of atoms does not condense into a liquid or a solid which is energetically favorable they are being cooled. Therefore the gas needs to be at very low density so the atoms interact very little. To complicate matters, as the density decreases, so does the temperature, at which the atoms will condense, ([7] eq.11.55). Practically, to keep the atoms at the low temperatures required for BEC and ultimately the atom laser, the atoms must be contained in a magnetic trapping potential. In contrast with phase transitions to liquid and solid states, which rely on inter molecular/atomic bonding, “BEC is unique in that it is a purely quantum-statistical phase transition, i.e., it occurs even in the absence of interactions” [6].

There are unique challenges with producing an atom laser compared to a photon laser. In a photon laser, photons are produced upon passing through the gain medium by invoking stimulated emission. After stimulated emission, the gain medium is in a lower state, this lower state has a short lifetime so absorption is minimized; as that would decrease the number of photons. For atoms, this presents a fundamental problem because atoms cannot be created by some process analogous to stimulated emission. Instead the atoms must already be present in the BEC. The next challenge is concerned with how to extract the atoms from the BEC in a highly controlled way to produce a laser, and is there a way of continually adding atoms to the BEC so the atom laser could be continuous?

In 1995 Wiseman and Collett published a theoretical description of an atom laser. They considered a 1-dimentional model and used dark-state cooling to cool the atoms down to their ground states. Such a state will not be excited while in an optical field because of quantum interference. So an atom in this state will not absorb energy from the optical field, but an atom in an excited state can be brought into a dark state through spontaneous emission. This aspect of irreversibility prevents the atoms from heating up during the cooling process.

This model proposes that the method for outputting atoms from the BEC to the laser beam would be from atoms tunneling out from the lowest mode of the magnetic trap. To replenish the collection of BEC atoms, atoms at a higher energy, would need to tunnel into the trap. These atoms would be incident on the trap from a thermal beam of atoms, and would fill upper modes in the trap. The atoms would then be cooled to the BEC by dark-state cooling. The problem with this idea is that the tunneling rates would be too slow for practical use.

In his 2002 paper from his Nobel lecture, Ketterle describes an experimental method of creating an atom laser. The cooling process breaks into two steps. An initial laser cooling process uses Doppler cooling until the atoms are cold enough to be contained in a magnetic trap. The atoms are then evaporative cooling until the BEC is reached. Evaporative cooling involves decreasing the potential of the magnetic trap. This allows the atoms with the highest energies to escape. Further, the atoms that remain can collide with each other, effectively readjusting the atom energy distribution. This allows for even more atoms to escape from the trap, carrying away energy with them.

Ketterle described that his group extracted collections of atoms from the BEC state using pulses of rf radiation. The idea is that the atoms in the BEC in the magnetic trap are trapped because their spins are all aligned so the magnetic trap confines them. The incident rf pulse on the BEC will flip the spins on some of the constituent atoms so they are no longer trapped. More precisely “Atom lasers are created by applying a rf field at about 38.6 MHz to transfer condensate atoms from the trapped state to the weakly anti-trapped state…” [4]. The spin flipped atoms then fall out of the BEC due to gravity. The atoms in each pulse are coherent with each other, but as they fall and gain momentum, the de Broglie wavelength decreases. In order to have constant de Broglie waves throughout the stream of released atoms, it is necessary to control the velocity of the beam. In this version of the atom laser, there is no gain medium analogous to a photon laser. Rather, the BEC has a finite amount of atoms in it and is depleted as the atom laser pulses are released from the trap.

It is possible to use a BEC as an active medium and “amplify” the stream of atoms in an atom laser. Unlike photons, atoms can only change their state, they cannot be created. The atoms in the BEC have a narrow spread of velocities which can be added to the beam of atoms.

“This transfer of atoms was accomplished by scattering laser light. The recoil of the scattering process accelerated some atoms to exactly match the velocity of the input atoms (Fig. 18). Not only were the atoms amplified, but they were in exactly the same motional state as the input atoms, i.e., they had the same quantum mechanical phase. This was verified by interfering the amplified output with a copy of the input wave and observing phase coherence.” [6].

While this allows for a mechanism to have an input stream of atoms and an “amplified” output stream, the mechanism to continuously bring atoms into the BEC is not described in the article. Depending on the magnetic trap being used to contain the BEC it is also possible to produce an output beam with a rf field. The properties of the out-coupler determine certain aspects of the output atom beam. The frequency of the rf out-coupler controls the de Broglie wavelength of the beam and the power controls the density of the beam.

With the ability to create a coherent beam of atoms brings the possibility to investigate new physics, and in particular, test how far the analogy between matter waves and E&M waves can be pushed, that is, the field of atomic optics. While the advent of atom lasers provides for new ways of exploring physics, there is still a lot of development needed to produce a robust atom laser.

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