A Beginner's Guide to the Atom Laser

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The atom laser is here and before long folks will probably want to own one. If you are the neighborhood physicist, your neighbor may ask for your advice on the best model. Your neighbor may even ask what an atom laser is. If you haven't kept up with the literature, this little guide could be helpful.

The first step in explaining the atom laser is to define "laser." In former years, this question wracked the laser community: ink was spilled, friendships lost. Today, things are fairly peaceful and you will not run into too much argument if you define a laser as simply a device that puts out laser light. Laser light is generally very bright, essentially monochromatic and highly directional. Unfortunately, that's not much use as a definition, since light from an extremely hot body that is passed through a good filter and collimator is also very bright, essentially monochromatic and highly directional. But it is not real laser light.

Here is how to tell genuine laser light from a cheap imitation. First, measure the frequency width of the spectrum, $\Delta\omega$. Then make a shutter device that passes a pulse of light for a time no longer than the correlation time $\tau_c = 1/\Delta\omega$. Count the number of photons, N, in the pulse. (If the photons come along too fast for your counter, it's okay to attenuate the light.) Repeat this many times. If N is essentially constant, you probably have a genuine laser. If it fluctuates wildly, your laser is a fake.

Our basic understanding of laser light is due to Roy J. Glauber, who developed the quantum theory of the laser field shortly after the laser was invented.[1] He gave the quantum state of the laser field its official name—the coherent state—though informally it is sometimes called the Glauber state. A field in the coherent state is as classical as quantum mechanics allows. The fluctuations in its amplitude and phase, for instance, are simultaneously as small as possible. Glauber also showed that the essence of laser light lies in its statistical properties. These

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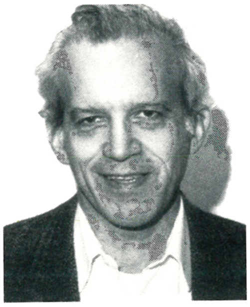

can be characterized by a hierarchy of coherences that govern the probabilities for observing twofold, threefold etc. coincidences in the detection of photons.

If we define a laser by the light it emits, then it follows that a laser is simply a source of radiation in the coherent state. There is one small flaw in this definition: Lasers operate in wavelength regimes from x-ray to microwave (where they are called masers). Evidently wavelength is of no fundamental importance. In the microwave regime, however, a host of devices such as klystrons and magnetrons can produce radiation in the coherent state. In fact, all oscillators produce radiation in the coherent state. Nobody would dream of calling these devices lasers. So our definition of a laser is not 100% reliable. However, we shall ignore the flaw because anyone who can't tell a laser from an oscillator should not be giving scientific advice to neighbors.

With this understanding of the laser, the definition of the atom laser is a cinch: An atom laser is a source of atoms in the coherent state.

The atom laser was made possible by the creation of a Bose–Einstein condensed atomic gas. The laser's debut occurred when Wolfgang Ketterle at MIT observed interference between atoms from two separate Bose condensates.[2] The atoms were released from the condensate by a magnetic resonance technique that permitted them to escape slowly through the potential barrier of the magnetic trap that confined them. The overlapping cloud of atoms from the two separate sources displayed clear interference fringes. The period was one half the de Broglie wavelength for, like light, the intensity goes through two maxima per cycle. It could be argued that thermal radiation also produces interference fringes, but that is only for light from a single source. For all practical purposes, separate thermal sources do not interfere. Light from two lasers can interfere, however, and so, Ketterle found, can atoms from two Bose condensates.

To put the interference fringes in perspective, their real significance is in confirming that the Bose condensate has long-range order, which suggests that the condensate atoms form a superfluid atomic gas. A superfluid gas is something new to physics. The atom laser is essentially a by-product of this discovery.

Interference demonstrates that there is a well-defined phase difference for atoms coming from different parts of a condensate, which is the usual definition of coherence (more precisely, first-order coherence). Furthermore, there is now strong evidence for both second- and third-order coherence.[3,4]

The fundamental difference between a thermal state and the coherent state is that in a thermal state the fluctuations in density are huge, whereas in the coherent state they are essentially absent. In a thermal state the probability of observing N particles instantaneously—that is, in a time short compared to the correlation time—is given by a negative exponential, which is about as broad as a distribution can be. In contrast, in the coherent state the probability of observing N particles is sharply peaked at the average value, and for large N the fractional spread in the distribution is essentially negligible.

Second-order coherence is a measure of the probability of detecting two particles simultaneously (or at some chosen separation in space and time). Such a process depends on the mean value of n^2. The density n has the same statistical properties as N. If the mean density, $\langle n\rangle$, is a large number, then in the coherent state, $\langle n^2\rangle = \langle n\rangle^2$, whereas in a thermal state, $\langle n^2\rangle = 2\langle n\rangle^2$. (The brackets indicate a spatial average.) Consequently, for a gas with a given $\langle n\rangle$, a second-order process is twice as rapid in a thermal state as in the coherent state.

Any atomic process that depends on two atoms being together—in other words, that depends on $\langle n^2\rangle$, can in principle be used to measure second-order coherence. In a Bose condensate, part of the system's energy arises from short-distance repulsions between the atoms. The interaction energy for a single atom depends on n, and so the energy of the system depends on n^2. If the trap is suddenly turned off, the atoms fly apart with a final kinetic energy that depends on the initial interaction energy. By measuring this energy, and measuring $\langle n \rangle$, it is possible to compare $\langle n^2 \rangle$ and $\langle n \rangle^2$. This method requires knowing the strength of the interaction. Fortunately at the low energy of a Bose condensate, the strength depends only on a single atomic parameter, the scattering length. For sodium and rubidium the scattering lengths are known from theory and low-temperature spectroscopic and collision studies.

An experiment on a Bose–Einstein condensate of rubidium by Eric Cornell and Carl Wieman at JILA yielded $\langle n^2 \rangle = (1.0 \pm 0.2)\langle n \rangle^2$; for sodium, Ketterle found $\langle n^2 \rangle = (1.25 \pm 0.58)\langle n \rangle^2$. Because the prefactors are obviously much closer to one than to two, these results represent strong evidence for second-order coherence. To be precise, the measurements confirm short-range second-order coherence. (The factor of two for a thermal gas has been observed by measuring the correlations in the arrival of ultracold atoms.[5] The factor decays to unity when the arrival time interval exceeds the system's correlation time.)

Should anyone still doubt that the condensate is in the coherent state, Cornell and Wieman have demonstrated short-range *third*-order coherence.[4] At high density the condensate can decay by a three-body collision. This is the process by which molecules are created in an atomic gas, the first step in the conversion of the gas to a solid. The three-body collision rate process depends on n^3, and for large $\langle n \rangle$, it is easy to show that in a thermal gas, $\langle n^3 \rangle = 6\, \langle n \rangle^3$. For a gas in the coherent state the factor of six would be absent. Cornell and Wieman compared the decay rates at temperatures below and above Bose condensation. They found that the rates differed by a factor of 7.4 ± 2.6, which agrees with the factor of six expected if the Bose condensate is in the coherent state and is in obvious disagreement with unity.

So, there is convincing evidence that atoms from the Bose condensate leave in the coherent state, which means that the system is fully qualified to be called an atom laser. In its operation, however, the atom laser is so different from a conventional laser that the name may seem slightly bizarre even if it is technically correct. But there is actually a close correspondence between nearly every detail of the two devices.

The source of photons in the optical laser (OL) is typically a gas or some other system of electronically excited atoms; in an atom laser (AL) the source is a gas of thermally excited atoms. In an OL the atoms radiate into a single mode by stimulated emission at a rate $\Gamma_0(k + 1)$, where Γ_0 is the spontaneous emission rate (the radiation rate into an empty mode) and k is the number of photons in the mode. In the AL the atoms scatter into a single mode (the ground state of the trap) at a rate $\Gamma_s(k + 1)$ where Γ_s is the rate of scattering into the empty mode and k is the number of atoms in the mode. In an OL the number of photons in a single mode is amplified by stimulated emission; in an AL the number of atoms in a single mode is amplified by stimulated scattering. In an OL the radiation is typically coupled out by transmission through one of the mirrors that defines the cavity mode; in an AL the atoms are coupled out by transmission through the potential barrier that defines the trap. The major difference between the two devices is that the photons from an OL generally emerge in a well-collimated beam, whereas atoms from the AL fly out in all directions. However, the difference is superficial. The OL operates in a high-order mode of the cavity whereas the AL operates in the ground state of the cavity (in other words, the trap). In this sense the AL is really closer to a maser than a laser, for the maser, operating in a microwave cavity, almost always operates in the cavity ground state. But who would want to own an "atom maser?"

If your neighbor happens to know that laser is the acronym for Light Amplification by Stimulated Emission of Radiation, you are likely to be asked how can one possibly apply the term to an atom emitting device. This provides an opportunity to display your historical expertise. In the early days when lasers first worked in the infrared regime, there was a proposal to call the device an iraser. And when the x-ray regime was broached, "xaser" was mentioned. Happily, these terms have disappeared. Instead, we have the infrared laser and the x-ray laser. And now we also have the atom laser. If your neighbor is obdurate, then explain that a more precise title would be Coherent State Atom Amplification by Stimulated Scattering of Atoms, or CSAASSA. "CSAASSA" does not roll lightly off the tongue, at least not off mine.

There is one more thing you must explain to your neighbor. Atoms are not photons. Atoms from an atom laser will not go far in air (in fact, today's atom lasers need ultrahigh vacuum), much less penetrate a glass window. Atoms fall under gravity and can bump into each other. As a result, applications of the atom laser appear to be rather specialized. However, if your neighbor is into serious atom interferometry or nanotechnology, or simply hankers to study a superfluid gas, then an atom laser might be just the thing.

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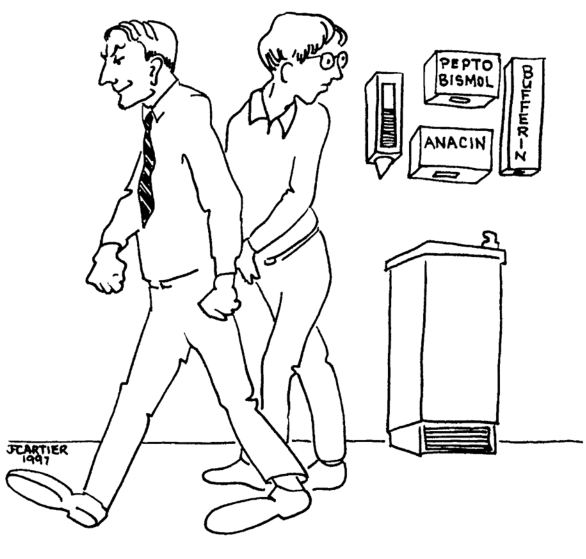

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