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A1_5 Laser Confinement of an Ideal Gas

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Abstract
Laser trapping is a technique widely used to confine atoms within a small region of space. In this paper, we present a model for such methods, in which radiative pressure from an EM source balances the kinetic pressure of the atomic gas. We calculate the limiting size of a gas confined in this manner and show that, for a 2 kW source, 10^{15} particles would occupy a volume of radius 1.27 m. The validity of the model is discussed, and we note that a gas containing more particles would fail to behave as an ideal gas.

The technique of cooling and trapping arrays of neutral atoms using radiation pressure from lasers is widely used in quantum physics experiments [1]. The most popular mechanism, *doppler cooling*, works by transferring the momentum of a photon when it is absorbed by the atom [2]. Due to the random motion of the atoms, it is equally likely that a photon will be absorbed by an atom moving away from the light source. This adverse effect can be overcome by tuning the frequency of the light slightly below the electronic transition of the atom. Hence, more photons are absorbed by atoms travelling towards the laser than away from it, allowing controlled cooling and trapping [3].

In this paper we investigate a simplified variation of the conventional mechanisms to trap an ensemble of neutral atoms using radiation pressure. A number of assumptions are made, and the validity of these is briefly discussed.

In our simple model, we consider an ideal gas containing N atoms which is confined within a sphere of radius R. We also assume that the ideal gas is a black body, so that all radiation is absorbed and the gas has no temperature gradient. It is surrounded isotropically by a source of EM radiation, for example an array of lasers, so that a power Γ is delivered to the atoms. Increasing this power will have two effects - the temperature of the gas will rise, causing a greater pressure pushing outwards and also causing greater cooling; conversely, the radiation pressure holding the gas together will also increase. There is thus a pressure balance between the two which we look to resolve.

To begin with, we find the temperature T for which the cooling rate balances the absorption rate - this is done simply by equating Γ with the right hand side of the Stefan-Boltzmann law. Rearranging, we find

$$T = \left(\frac{\Gamma}{\sigma A}\right)^{1/4} = \left(\frac{\Gamma}{4\pi\sigma R^2}\right)^{1/4}, \tag{1}$$

where σ is the Stefan-Boltzmann constant and the surface area A has been substituted for in terms of the radius R of the gas cloud.

Next we consider the pressure balance. The radiation pressure P pushing in will be given by the standard relation for EM radiation $P = I/c$ where I is the intensity. If a constant power is being delivered, the intensity will fall off with the surface area and hence the inwards pressure will be given by

$$P_{in} = \frac{\Gamma}{4\pi c R^2}. \tag{2}$$

Similarly, we need to know the pressure outwards. As our model utilises an ideal gas, this will be given by the ideal gas law for a fixed number of atoms: $PV = Nk_BT$. In terms of the radius, this is

$$P_{out} = \frac{3Nk_BT}{4\pi R^3}. \tag{3}$$

A stable situation will occur when the radiative pressure inwards balances the kinetic pressure outwards. This will be the point at which the ideal gas can be said to be confined. We thus equate the right hand side of equations 2 and 3 and then substitute in for the temperature using Eq. 1. After some manipulation, the relationship is found to be

$$R = \left(\frac{3ck_B}{\sigma^{1/4}(4\pi)^{1/4}} \right)^{2/3} \frac{N^{2/3}}{\Gamma^{1/2}} \tag{4}$$

between the radius of the spherical gas distribution, the power used to confine it and the number of particles:

$$R = 56.7 \times 10^{-10}\ \mathrm{W}^{1/2}\mathrm{m} \left(\frac{N^{2/3}}{\Gamma^{1/2}} \right). \tag{5}$$

What does this translate to physically? A laser is considered to be reasonably powerful if it is able to deliver around 2 kW. If we let $N = 10^{15}$ as an example case this gives a radius of 1.27 m, resulting in a density in the confined sphere of 1.17×10^{14} m^{-3}. This value is sufficiently low that the ideal gas assumption is valid. If N is much smaller, however, then the density will become so great that the ideal gas law no longer applies, and so the model may not be valid in regimes of very low N.

The model presented contains many limitations, some of which should be investigated. Firstly, the use of an ideal gas is unrealistic. In such arrays the density may be very high and a van der Waals gas may be more suitable in such a case. More importantly, the approximation that the EM radiation is delivered isotropically is clearly unrealistic - in fact, most real trapping systems will use highly focused lasers and this will likely have significant effects on our model.

References

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