Optical Molasses—C.E. Mungan, Fall 2003

An interview with Steven Chu, the 1997 Nobel prize winner, in American Scientist **86**, 22 (Jan–Feb 1998) contains some simple estimates of the physics of slowing atoms down with light. These estimates are very easy to derive and make a nice Modern Physics problem:

1. Chu says that every time an atom absorbs a photon from a laser, its speed slows down by 3 cm/s. Prove this, assuming the atom is part of a monatomic gas of sodium and the optical source is a counter-propagating diode laser nearly resonant with the D line (in the mid-visible range). This implies you can optically trap the atoms for about a second within a 1-cm diameter volume due to its Brownian diffusional motion.

2. Next, suppose that an atom absorbs and emits a photon every radiative lifetime ($\tau = 3\epsilon_o m_e c\lambda^2 / 2\pi e^2 = 16$ ns from the Lorentz oscillator model). Consequently, verify that the average optical force on an atom is approximately 200 000 times the force of gravity.

3. Chu concludes that a room-temperature atom can be stopped within a millisecond. Show that this is correct, assuming the laser to be of sufficiently high intensity. (Hint: Assume that the atoms are initially traveling at their room-temperature rms speeds as given by kinetic theory for a monatomic ideal gas.)

4. What is the minimum temperature to which you can cool the gas owing to recoils from the scattered photons?

5. Bonus question: How intense must the laser be to stop the atoms this quickly, assuming circularly polarized light (for which the resonant absorption cross section is $\sigma = 3\lambda^2 / 2\pi = 1.7 \times 10^{-9}$ cm^2)?

Solutions:

1. $\Delta\upsilon = \dfrac{p}{m} = \dfrac{h}{m\lambda}$ at $\lambda = 589$ nm for Na ($m = 23$ g mol^{-1} / 6.022×10^{23} mol^{-1})

2. $\dfrac{F_{\text{optical}}}{F_{\text{gravity}}} = \dfrac{m\Delta\upsilon/\tau}{mg}$

3. $F_{\text{optical}} = ma = m\dfrac{\upsilon_0}{\Delta t}$ where $\frac{1}{2}m\upsilon_0^2 = \frac{1}{2}kT$ (noting that υ_0 refers only to the component of the initial velocity in the laser beam's direction) so that $\Delta t = \upsilon_0\tau / \Delta\upsilon = 0.2$ ms

4. $m(\Delta\upsilon)^2 / k = 2.4\ \mu$K (in contrast to the Doppler cooling limit of $\hbar / 2k\tau = 240\ \mu$K)

5. $I = \dfrac{hc}{\lambda}\dfrac{N_{\text{abs}}}{\sigma\,\Delta t} = \dfrac{hc}{\lambda\sigma\tau} = 13$ mW / cm^2 (double the saturation intensity) where the number of absorptions each atom must undergo to stop is $N_{\text{abs}} = \upsilon_0 / \Delta\upsilon$